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CALIBRATION CAPABILITIES OF THE ESF INSTRUMENT BRANCH

C. L. Owens

ARO, Inc.

March 1967

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NOTICES

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FOREWORD

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This technical report has been reviewed and is approved.

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ABSTRACT

To gather the required performance test data at the AEDC, a complex network of test instrumentation and data gathering equipment must operate as a system. Reliable test data depend upon the reliability of each individual unit of the system; therefore, known standards must be established to meet specific requirements. In addition, various research groups are engaged in special projects often requiring some accuracy level in the measurement of physical variables. In today's technology of the space age, pressure is continuously exerted to obtain greater performance from all systems. Increased performance of complex systems and the necessary interchangeability of components require measurements of known accuracy or compatibility in a variety of quantities. The purpose of this document is to present the hierarchy of measurements for various units that are derived from national standards and disseminated through the ESF Instrument Branch. This information should enable the users of measuring equipment to better know the capability of their equipment and to have confidence in the results obtained by specifying the level of calibration desired.

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SECTION I
INTRODUCTION

The end result desired in many of our scientific endeavors of a test or research nature is the description and prediction of the behavior of a given physical system. The ability to predict the behavior of a system is very dependent upon the completeness with which the system is described. The use of mathematics is an efficient means of describing a given system. The measurement of physical variables in terms of numbers and units that determines the states of a system is essential to the mathematical description.

The measurement of a physical variable is usually performed by the observation of the state assumed by a measurement scale when the scale bears a particular relationship to the system being described. A simple example is the use of a mercury-in-glass thermometer. The state of a particular system may be dependent upon the physical variable, temperature, to a considerable extent. When such a system is in thermal equilibrium with a mercury-in-glass thermometer, the number assigned to the temperature of the system is that found adjacent to the end of the mercury column.

The ideal measurement scale should possess two definite characteristics. First, to each number or scale point, there should correspond one, and only one, value of the physical variable. Second, the number assigned to a particular value of the variable should be independent of the measurement scale employed. Practical use of measuring instruments precludes the realization of these two ideal conditions. Generally, it is not possible to distinguish between arbitrarily close neighboring states of the measurement scale. For each number on the scale there exists not one value, but a finite range of values of the variable. The second ideal characteristic could be realized if the scale points of all existing measurement scales of a particular type were multiples of some universal unit. Since such units usually correspond to discrete states of a system, it is not possible, in the practical sense, to construct a scale on which all points represent exact multiples of the unit. Therefore, if the description of a given system is based upon measurements performed with a particular scale which is to be used in the description of other similar systems, or in the description of more complex systems of which the given system is a part, the extent to which points of the scale deviate from multiples of the unit must be known.

From the above discussion one fundamental fact is salient: in all measurements an error or uncertainty is always present and must be

considered in the final analysis. It is a function of the group responsible for the maintenance and use of calibrating standards to supply the user of measurement scales with a knowledge of the two limitations noted above. Accuracy is simply the degree of certainty that can be attached to measurements, and the quality of measurements is determined by the degree of certainty or confidence that can be attached to them.

It is the responsibility of the National Bureau of Standards (NBS) to establish and maintain the basic standards of the nation (Ref. 1). By careful construction of equipment, rigid control of environmental conditions, and the application of established physical and mathematical laws it is possible to precisely determine the inherent limitations of these measurement scales. The types of calibration obtainable from NBS makes available secondary, tertiary, and other scales that have been compared with the NBS primary standard scales and whose scales have been specified within known limits as corresponding to certain numbers of absolute units. In keeping with general government policy, NBS provides calibration services only for standards of the highest quality and provides only those services which the laboratories cannot reasonably be expected to provide for themselves or to secure elsewhere (Ref. 2). Because of this limitation, it is not economically feasible for the engineer who is continually faced with measurement problems to deal directly with NBS. A more efficient procedure is the establishment of an intermediate laboratory having a group of units and scales with which the engineer's working scale may be frequently and conviently compared.

If an intermediate laboratory is expected to perform the calibration of instruments having accuracy ratings of 0.1 percent or better, high accuracy standards of known long term stability are required. Such an operation is usually referred to by the term "standards laboratory". Of necessity, any standards must originate in an unbroken chain from the National Bureau of Standards. Several criteria for a good standards laboratory are discussed in Ref. 2.

Such an intermediate or standards laboratory is concerned with the process of measurement of physical quantities which involves a series of steps in which the units of measurement are transferred by means of measuring apparatus designated as some type of standard to the actual instrument used for measurement of the quantity. These standards are standardized by comparison with standards of a higher level and in turn used to standardize measuring equipment of a lower level. This succession of steps from the highest level of precision and accuracy to the lower level of actual measurement is known as the calibration process.

Recently, a magic word, "traceability", has found widespread usage, and since there has been no accepted definition or clarification of the concept, a certain amount of confusion has resulted. It is possible to devise a system which ensures that every measurement in the system is derived from a national standard, but there is no guarantee of accuracy of measurement in the system. The word traceability is many times applied to just such a system. Since accuracy of measurement is dependent on many factors, the concept of traceability will be limited to the establishment and maintenance of a suitable system. For any system, traceability to NBS (when possible) is a necessary but not sufficient condition for obtaining consistency and accuracy. An important part of the system consists of maintaining adequate records of the standards used in each step of the calibration process. This will allow documentation of the links in the chain back to NBS. Traceability does not require that measurements be directly and immediately referred to NBS by means of a single link. The chain can have any number of links or steps between NBS and the measurement being made provided each step is adequately documented and reasonable additional tolerances are allowed for each step.

SECTION II
METHOD OF OPERATION

In the operation of a calibration laboratory, those responsible for its operation have a continuous task of evaluating the results of their work. This is necessary because of the national emphasis on better and more reliable measurements to support complex missile and space programs. Personnel trained in both physics and engineering are employed since a rigid technical attitude must be maintained.

Present standards were procured to satisfy the requirements of various groups. If there are areas of measurement that are not shown, the ESF Instrument Branch should be contacted and these requirements made known. An effort will be made to develop the necessary capabilities to support a given type of measurement. The users of the information can be quite helpful in determining whether or not the calibration program satisfies their measurement requirements.

There is much variation in the methods and procedures for operation of a calibration laboratory from one company to another. The methods and practices used are to a large extent determined by the overall work program of the parent organization. Some of the requirements for the operation of a calibration laboratory are described below.

First, the position of the laboratory in the organization and its function should be adequate for its intended purpose. The end product here is test data; therefore, every effort should be made to guard against the propagation of errors in each measurement chain. The need is evident when it is realized that the end product is no more accurate than the standards used for calibration.

Second, the laboratory should have adequate facilities and equipment and must maintain the proper physical environment. When new requirements are received, or accuracy improvements are required, efforts are channeled in this direction. It should be realized that there is a time lag in establishing a measurement capability after the requirement is known. This shortcoming is a necessary condition because the knowledge, experience, competence, and morale so important in a calibration laboratory do not have the response of an electric light. A new capability must be carefully developed and maintained.

Third, the preservation of accuracy requires the segregation of reference standards from lower level standards and that they be used only as reference standards. In some areas this is becoming increasingly difficult because production tolerances are such that accuracy requirements can be met only by using reference standards as a working standard. This is not good practice because any standard that is subjected to everyday use ceases to become a reliable standard. It is desirable to procure duplicate sets: one to be used on a working basis and the other held in reserve for frequent intercomparisons.

Fourth, the laboratory's reference standards should be calibrated in terms of the national standards. This is accomplished by sending standards to NBS or DOD Standards Laboratories. In many instances an interlaboratory standard, separate from the reference standards, is used for comparison with the national standard. The interlaboratory standard is compared with the reference standard before shipment to a higher level laboratory. It is again compared after return to the local laboratory. In this way any changes during shipment may be detected. If these successive intercomparisons show no change in the interlaboratory standard, then its most recently assigned value may be assumed correct and the reference standard adjusted accordingly. This required an additional expenditure for standards; however, it is felt that the additional accuracy and confidence is adequate justification. Also a realistic recalibration interval for the reference standard can be chosen.

Fifth, the calibrations performed by the laboratory are within the accuracy and error limits claimed. This accuracy is dependent upon the quality of standards, personnel performing the calibrations, and the

quality of measurement systems. This requires constant monitoring of calibration information to note variations in results. When possible, results of calibrations performed in the laboratory are compared with results obtained in other laboratories having comparable standards. Laboratory personnel visit NBS and other standards laboratories to compare methods used and results obtained. In those areas where no standards are available it is necessary to develop methods of calibration using proven techniques until such standards become available.

Instruments alone do not make the measurements. Trained personnel working in the proper environment are the factors that determine the measurement quality of a laboratory.

The servicing of an instrument includes calibration and maintenance. Separation of these efforts into two distinct areas is difficult, since they are so closely allied. In many cases, calibration will show a need for maintenance and the need for maintenance results in the need for calibration. For this reason, when an instrument is received for servicing, calibration and/or maintenance is performed as required.

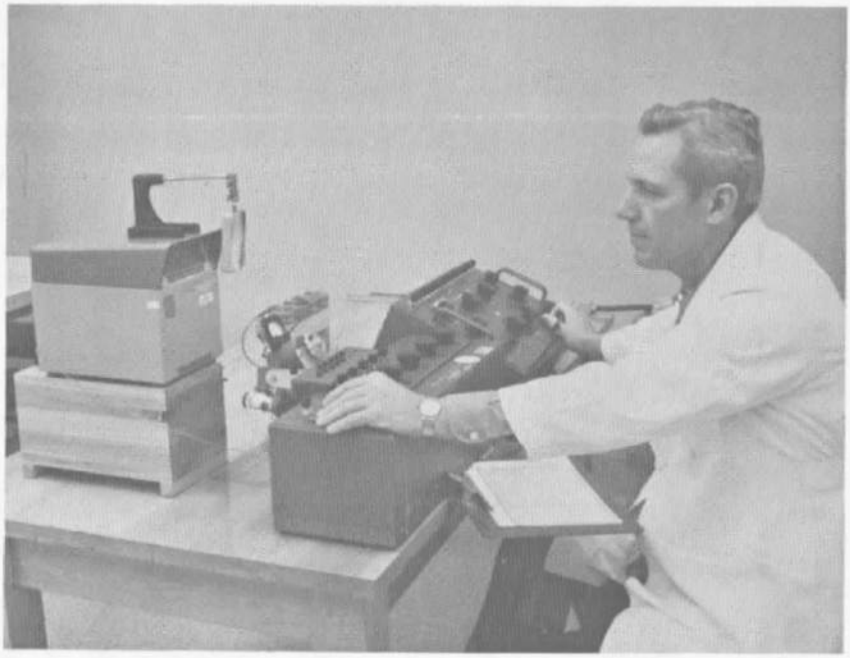
In the following sections, the basic capability and traceability charts for the various units of measurements are presented. Also included are brief discussions of the measurements and photographs of some operations.

SECTION III
ELECTRICAL MEASUREMENTS

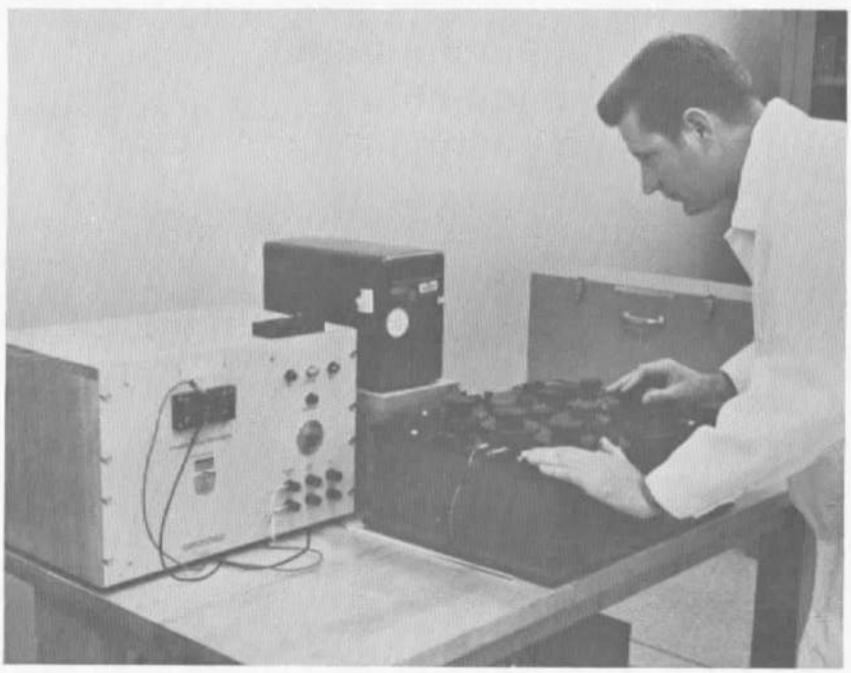
The basic electrical measurements capability and traceability chart is shown in Fig. 1, page 11.

The basic units of the volt and ohm for the United States are maintained by NBS. For compatability of measurements, science and industry must use these units as a reference base. To extend these units in both directions, ratio devices afford a convenient method. These ratio devices, shown as ratio sets in Fig. 1, are not considered standards by definition, and are not directly related to the nationally maintained units. The present practice is not to refer these devices to NBS for calibration.

The user can calibrate a ratio device himself. The self-check method applied to a ratio device consists essentially of an intercomparison of a number of nominally equal parts of the device on a



Ratio Techniques are Used to Calibrate Laboratory Potentiometers.



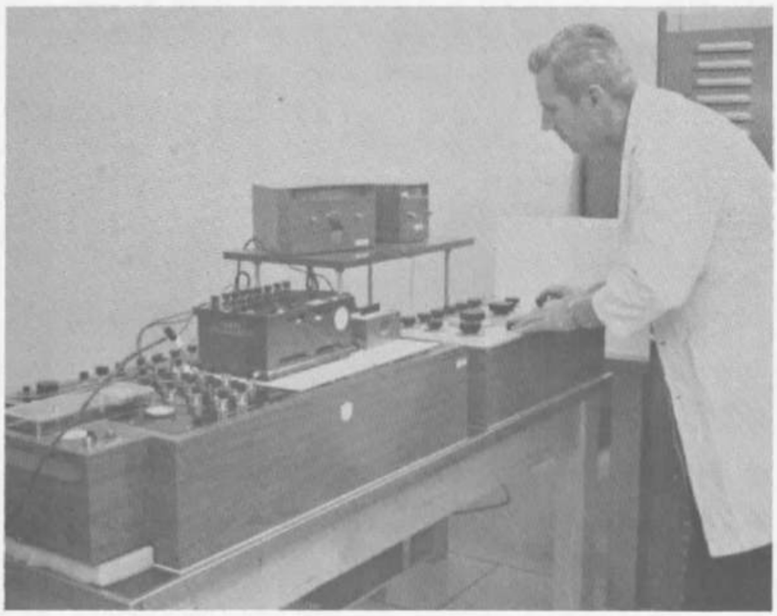
Unsaturated Standard Cells are Compared with Reference Standard Saturated Cells.

one-to-one basis. For example, in many devices it is a comparison of ten steps on one dial to each step of the next higher decade. The end results are combined by arithmetic processes to provide corrections for combinations of the various parts. The quality of the results can be checked by using various combinations of standard resistors. Such a procedure is more economical from the standpoint of time and money and allows the user to learn firsthand more about the capabilities and limitations of his equipment.

After calibrating the ratio sets, a means is available for extending the scale of resistance measurements up or down in terms of the resistance values of known standards. In addition, other ratio devices such as a potentiometer or volt box may be calibrated by using the calibrated ratio sets. In this manner, the voltage scale is extended from very small values to quite large values. These devices simply measure the ratio of an unknown emf to that of a standard cell.

Also shown on the chart is a Kelvin bridge with calibration by a higher level laboratory. This is purely an economic factor. The quantity of low resistance calibration work presently being performed does not justify the expenditure required for precise steps back to low resistance standards.

The measurement of current in terms of known values of resistance and voltage covers a wide range of d-c currents. At the low end of the scale the accuracy is limited by the sensitivity of the equipment. At the



Secondary Standard Voltboxes are Compared
with the Reference Standard.

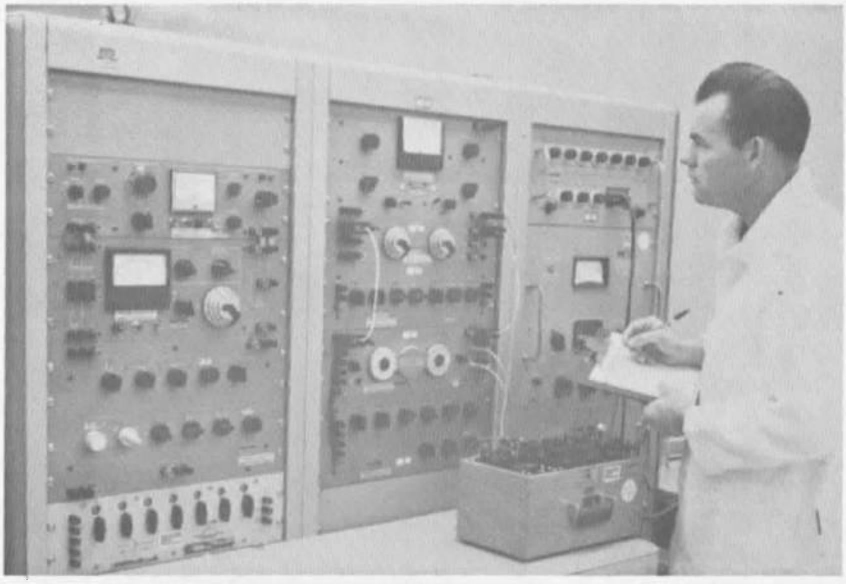
Rapid Calibration of Electrical Indicating Meters is Possible Using Specialized Equipment.

high end of the scale, convenient standards are available in the form of multirange shunts. The basic units are sent to a higher level laboratory for calibration.

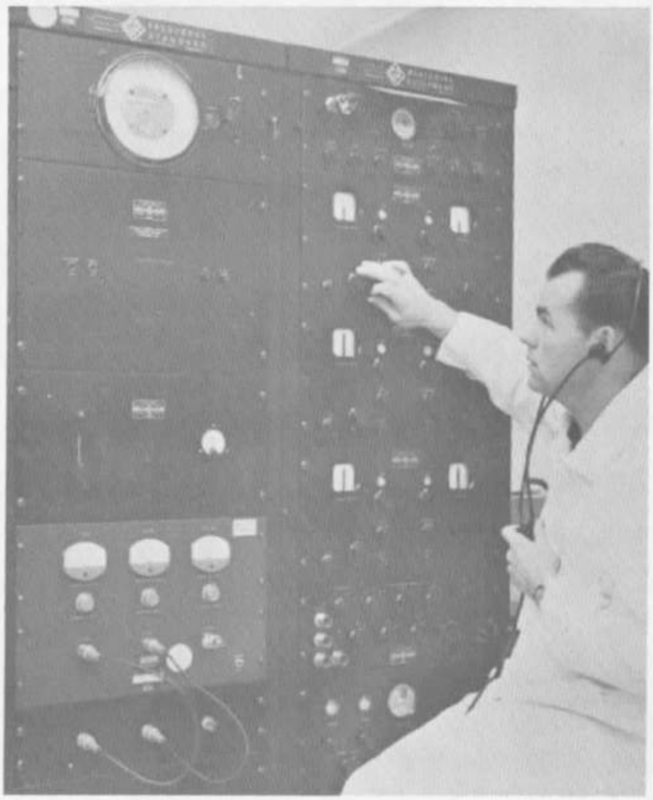
The units of current and voltage derived from standard cells and precision resistors are applicable to the measurements of d-c quantities only. Of equal importance is the measurement of a-c voltages and currents. To make this transfer, a thermal converter is used. This is essentially a device that responds to the heating effect of an electrical current. NBS provides an a-c - d-c difference determination. Because the a-c - d-c difference depends on geometrical factors that are relatively permanent, subsequent tests for checking the constancy of calibration can be made on direct current.

These basic units make it possible to perform many routine calibrations on a comparison basis for a wide variety of electrical and electronic devices. The a-c - d-c meter console is used for the routine calibration of indicating meters of 0.5-percent accuracy or less. The electronic calibration console provides a high accuracy capability in the measurement of d-c and low frequency parameters.

Standard frequency and time broadcasts from NBS are used to standardize the frequency of a quartz oscillator. This primary frequency standard provides a range of standard fixed frequencies.

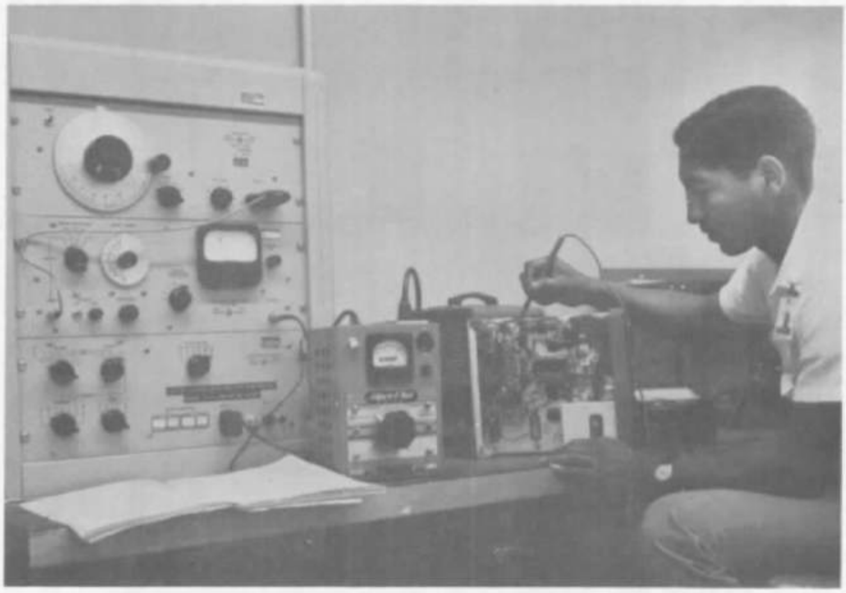


An Assembly of Precision Components is Used for the Calibration of Many Types of Electrical and Electronic Instruments.



Frequency and Time Standards are Calibrated with Standard Transmissions.

To measure unknown frequencies, it is necessary to have some means of evaluating the unknown in terms of a standard frequency. The frequency measuring equipment is designed for this purpose. It is then possible to calibrate oscillators and counters to provide sources of known frequencies for day-to-day laboratory work.



Maintenance and Adjustment of Equipment are Performed Prior to Final Calibration

Repair of a Wide Variety of Electronic Equipment is Performed

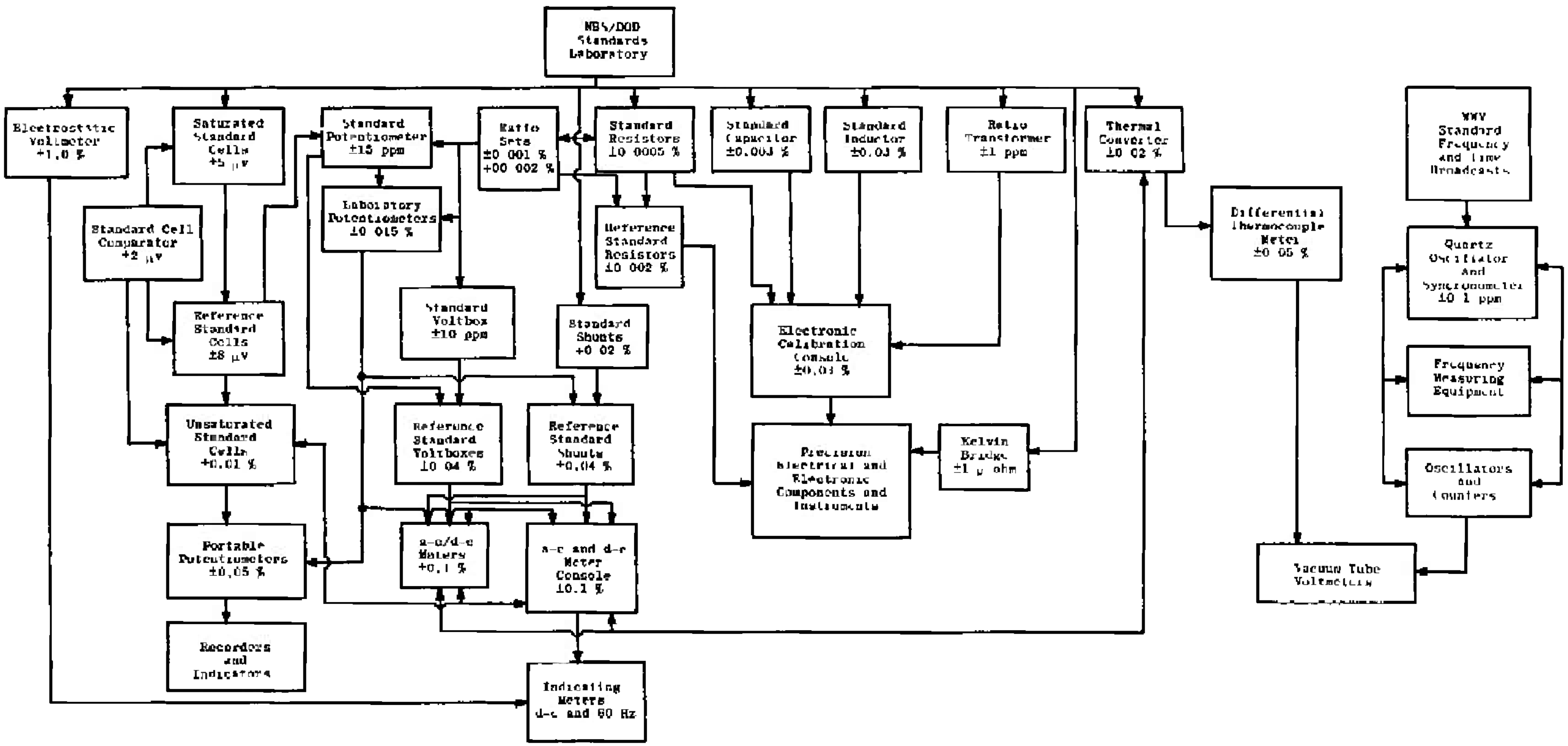


Fig. 1 Basic Electrical Measurements Capability and Traceability Chart

SECTION IV
PRESSURE MEASUREMENTS

Pressure measurements are frequently made to describe the static or dynamic behavior of fluids. Pressure is defined as force per unit area. This pressure is a positive quantity. It is known that under exceptional circumstances a liquid can withstand a tensile force, a negative pressure of the nature of a pull across a surface. However, in this discussion, pressure will be treated as a positive quantity which is sufficient for engineering and technical purposes. It can also be shown that at a given point in a static fluid, the pressure is independent of the direction of a surface through the point. Thus, pressure in a fluid can be treated as a scalar function of position.

Pressure instruments are usually used for the measurement of the pressure exerted by a fluid. These measurements may be classified as follows:

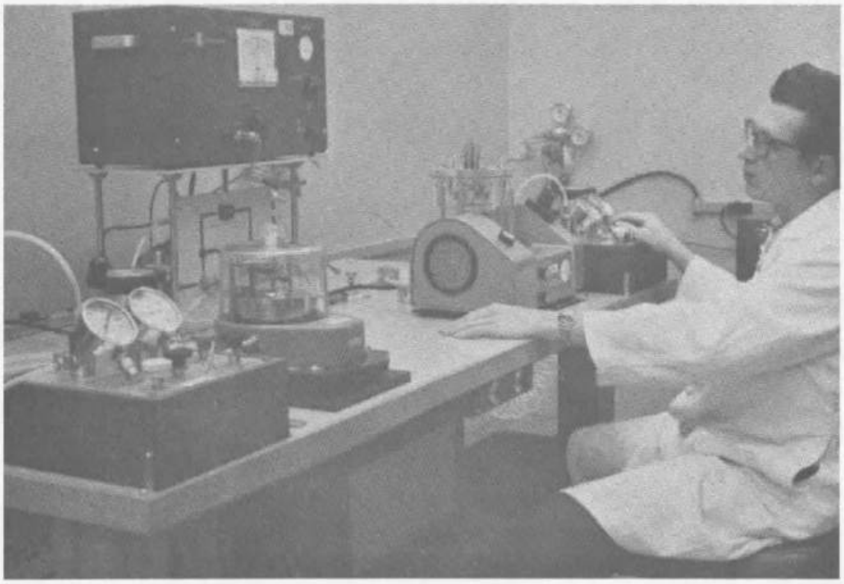
1. Absolute pressure, which is the total pressure; this is the pressure measured when the reference approaches a perfect vacuum.
2. Differential pressure, which is the difference in pressure of a fluid at two different levels.
3. Gage pressure, which is the differential pressure referenced to that of the surrounding atmosphere.

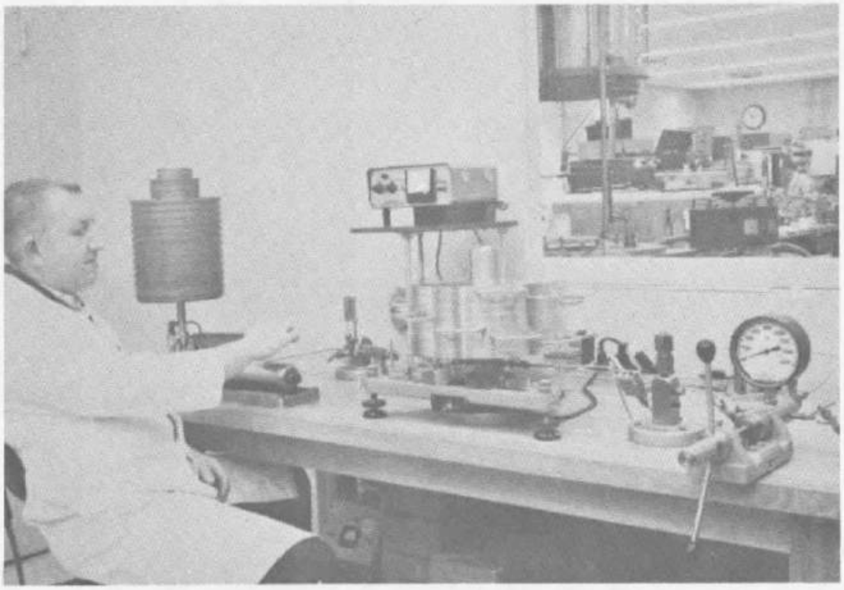
As an example of the above classifications, consider the height of a liquid column representing the pressure existing between the two menisci. This is a measurement of the differential pressure existing between the two menisci. If the pressure above one meniscus is zero, then it becomes an absolute pressure measurement. If the pressure above one meniscus is atmospheric pressure, then the measurement is gage pressure.

The basic pressure measurement capability and traceability chart is shown in Fig. 2, page 18. The units of pressure are transferred from a higher level laboratory by means of standard deadweight piston gages except for the micrometer manometer which is calibrated with dimensional standards.

Air and oil deadweight piston gages are used to cover the pressure range up to approximately 12,000 psi. The unit sent to a higher level laboratory (interlaboratory standard) is used for the sole purpose of establishing units of pressure locally. Duplicate items (reference standards) are calibrated by comparison with the interlaboratory

standard. This is in keeping with the policy of segregating standards, as any standard subjected to everyday use ceases to become a reliable interlaboratory standard.



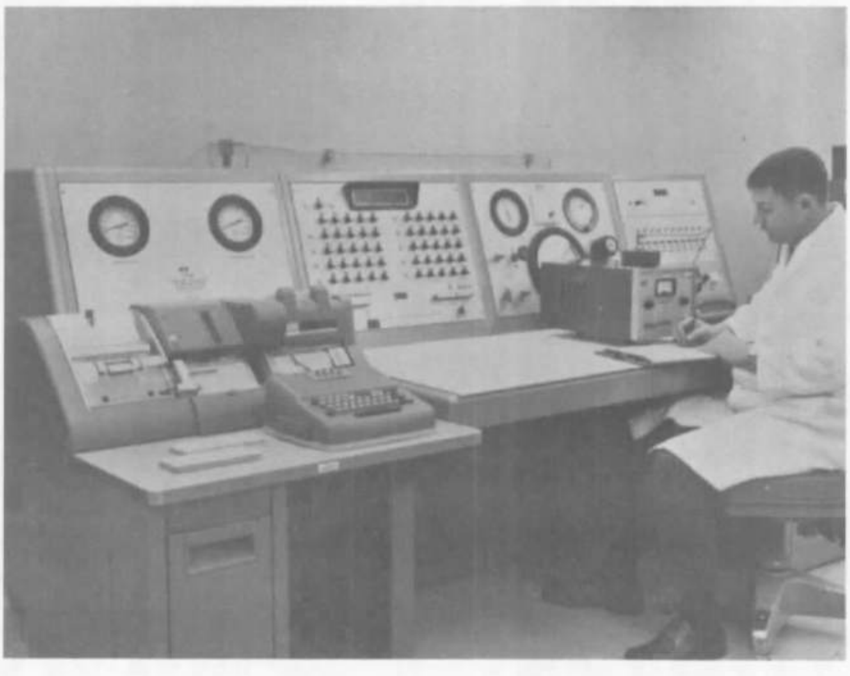


Intercomparison of Air and Oil Deadweight Piston Gages

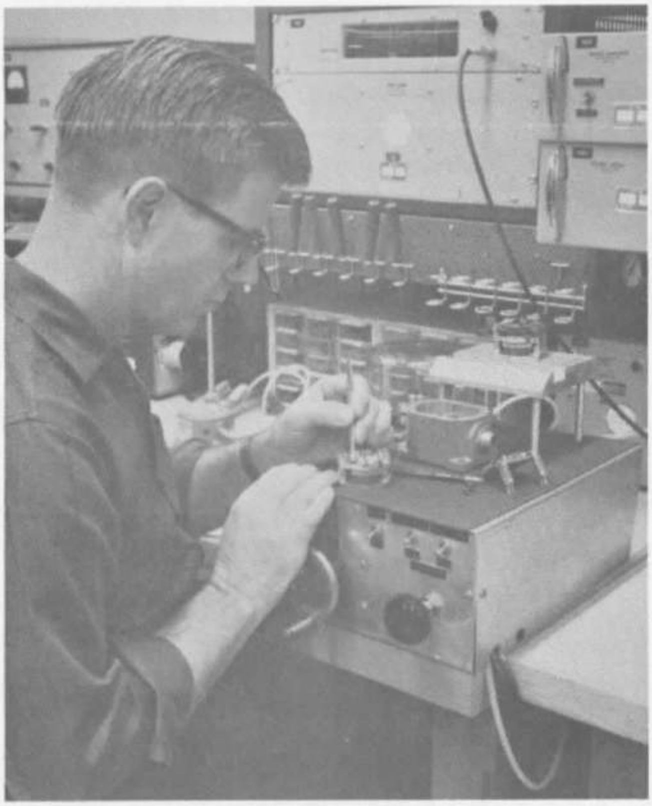
The reference standard gages are then used to calibrate other piston gages as well as other precision pressure measuring devices. Using these lower level standards, a wide variety of pressure instrumentation equipment is calibrated.

The pressure transducer calibrators shown on the diagram are three independent systems. The range of pressures from 1.5 to 500 psi uses nitrogen as the pressure medium. The device used for determining pressures applied to the transducer is a precision pressure balance having an adjustable analog output voltage. Linearity and hysteresis values can be precisely determined by measuring small differences in output voltages between the pressure balance and the transducer under test. Pressure and electrical calibration of the components is performed daily or just prior to use. The total system error is estimated at ±0.36 percent at the low end and decreases to ±0.1 percent at the higher ranges.

For the calibration of pressure transducers in the range 500 to 10,000 psi, an oil deadweight piston gage is used as the pressure source. The electrical characteristics are determined by a ratio comparator. The ratio comparator is used to establish the ratio of output to input (millivolts per volt) at full scale of the transducer being calibrated. The percent of full-scale output at other pressures is then determined. System accuracy is estimated at ±0.15 percent.



Calibration of the Automatic
Pressure Transducer Calibrator



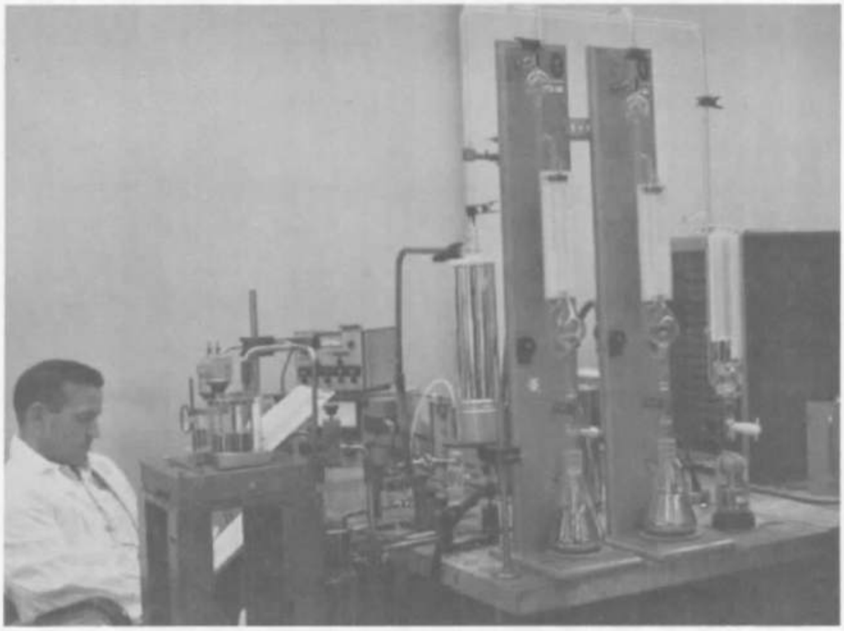
Complete Repair Service is Peformed on
Some Types of Pressure Transducers.

Another system recently obtained for the calibration of pressure transducers uses two air deadweight piston gages for developing known pressures up to 5999 psi. The system can be programmed for automatic operation. Calibration data are in the form of IBM punched cards. Data presentation is obtained from the computer printout. Total system error is estimated at ±0. 1 percent.

In the area of pressure measurements known as "vacuum", "high vacuum", and "ultra-high vacuum", there is a lack of recognized national standards, and traceability is not as straightforward as the measurements discussed above.

There are available on the market a large number of devices for making vacuum measurements. These devices are capable of reading pressures over several decades. In fact, some of the gages are such that it is not a simple matter to produce pressures as low as the gage can indicate. A calibration activity is faced with the problem of not being able to have vacuum gages standardized by NBS to cover the range of measurements that the laboratory is called upon to make.

To perform calibrations below one micron, methods must be devised that have a sound basis and produce repeatable results. Then no blanket guarantee can be made for these low pressure readings, and traceability to national standards is almost nonexistent. As soon as a suitable gage can be procured, it will be sent to NBS for calibration over the range of one micron to one torr.



Micrometer Monometer and McLeod Gage System

The micrometer manometer is a specially constructed differential device so that one side can be referenced to a pressure of 10^{-5} to 10^{6} torr, making it an absolute manometer. The calibration of the two-depth micrometers is referenced to dimensional standards. Experience with this device indicates that a tolerance of ±0.01 torr is possible. However, this results in an error of one percent at one torr, which is quite large when compared with the manufacturer's stated accuracy of some devices operating in this range.

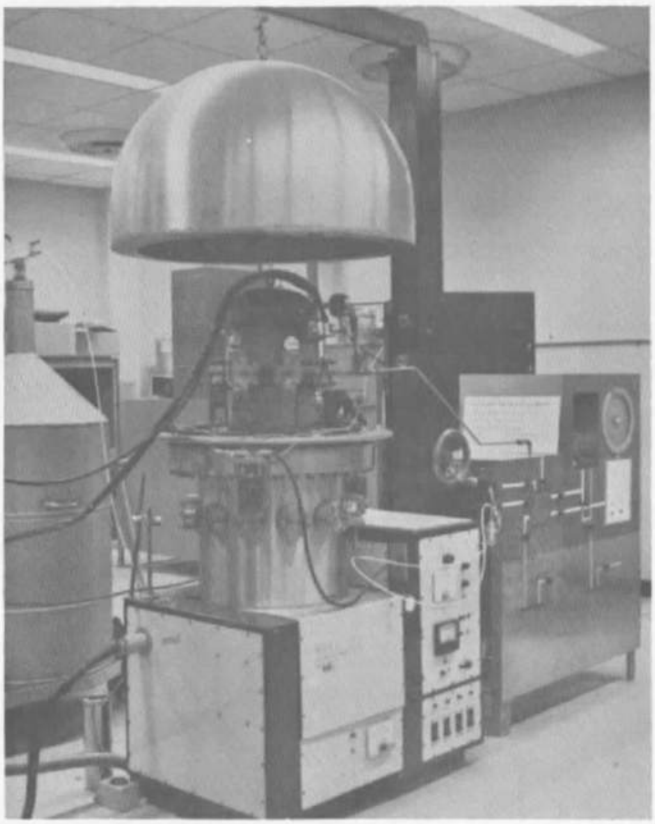
The McLeod gage has found the most widespread usage for low pressure measurements in spite of its shortcomings and will continue to be used until a more dependable standard is available.

To extend the pressure scale to lower values, a comparison of two gages over an interval common to both is accomplished. This does not constitute a valid and traceable calibration, because no absolute accuracies of a usable magnitude can be derived, only an estimate of the agreement between gages as the measuring scale is extended to lower

values. For example, the 0.01 to 2.0 torr McLeod gage is compared with the micrometer manometer over the common range. The process is continued between successive gages to cover all ranges. This explains the lack of high accuracy standards in the portion of the chart covering vacuum measurements.

For the calibration of gages below 10^{-3} torr (1 micron) the lack of a standard is even more critical. It has been a general practice to calibrate the gage by comparison with a McLeod gage at the upper end of the scale and then extrapolate over several decades. This has not proven satisfactory.

One method that is receiving some acceptance is what is known as "the dynamic method". The basic principle employed is that of producing a pressure in a test volume that is directly related to a measurable pressure in another volume. The high vacuum calibration system shown in the chart uses this method. Pressure reduction by a factor of approximately one million is accomplished by using two conductances in series. The porous plug is a very small conductance that is calibrated by measuring the time required to evacuate a known volume from one known pressure level to another.



High Vacuum Calibration System

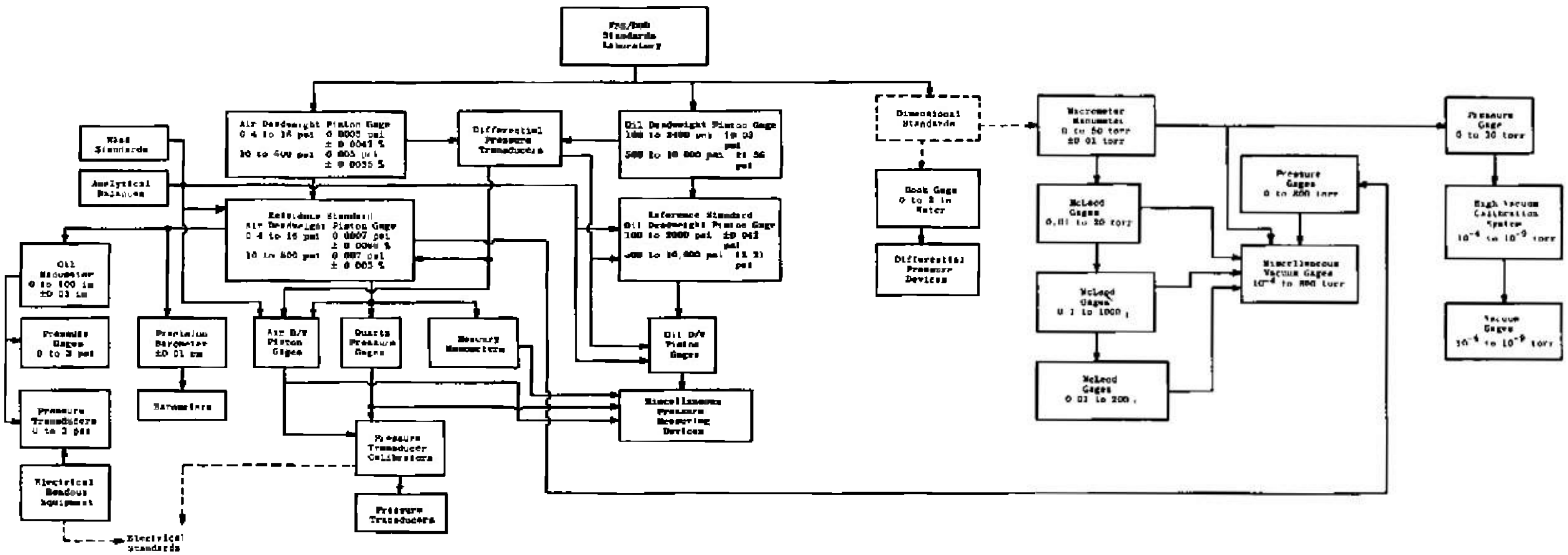


Fig. 2 Basic Pressure Measurements Capability and Traceability Chart

SECTION V
TEMPERATURE MEASUREMENTS

Temperature is one of the fundamental quantities which from the basis of our scientific measuring system. The unique characteristic of each of these quantities is that the physical standard for any one of them may be changed independently from time to time with no effect on the others. For example, changes in the length of the second are not reflected in the standard kilogram, meter, or the triple point of water. Temperature scales in common with length scales, weighing scales, and other measuring scales are references to which a quantity can be compared. A comparison of two or more temperatures to the scale allows the difference between them to be determined in the scale units. In general, scientific measurement is involved with two scales of temperature - the thermodynamic scale and the practical scale.

The thermodynamic temperature scale is fundamental, that is, it is independent of the properties of any substance. In the strictest sense, the equations of any thermodynamic system are exact only for temperatures on this scale. Experimentally, the thermodynamic scale is by its nature difficult to establish. As a result, the accuracy of measurement on this scale is not as high as the precision of measurement on some arbitrarily defined practical scales.

To overcome this difficulty, a practical scale has been formulated and is in general use by international agreement. This scale, the International Practical Temperature Scale (IPTS), was defined and designed to represent the thermodynamic scale as closely as possible above -183°C. The IPTS is based on assigned values for six reproducible equilibrium temperatures (fixed points) and the mathematical equations establishing the relation between temperature and the indications of instruments calibrated by means of the fixed points. The values assigned to these points are only approximate true thermodynamic values, and the formulas specified are empirical. As such, the scale is subject to revision and improvement from time to time as more accurate methods of measurement are evolved.

The thermodynamic scale and the IPTS are linked by definition to be exactly the same value at one temperature - the triple point of water (273.16°K, 0.01°C). This point has been found to be one of the most reproducible in nature. Current measurement techniques indicate that its reproducibility is better than 0.0001°C. Differences between the thermodynamic and practical scales range from 0 deg at 0.01°C to about 14 deg at 5000°C.

In addition to the IPTS there is another practical scale which is coming into widespread use in the United States. To cover the range from -263 to -183°C, the National Bureau of Standards maintains a provisional scale, NBS-55. Though this is not internationally accepted, it does provide for uniformity in low temperature measurement throughout the United States.

The basic temperature measurements capability and traceability chart is shown in Fig. 3, page 23.

Platinum resistance thermometers are used as interlaboratory standards for establishing the scale locally over the range -263 to 630°C. One of these thermometers covers the range -183 to 630°C. The other thermometer covers the range -263 to -183°C on the NBS-55 scale. The Mueller bridges used with the resistance thermometers are ratio measuring instruments and can be calibrated using ratio techniques. With care, the bridge can be used to an accuracy of about ±0.001°C. The bridges are used to make a comparison between the interlaboratory and reference standards.

A Resistance Thermometer is Checked at the Triple Point of Water.

Low Temperature Calibration System

In the laboratory, better results are usually obtained when the standard and test thermometer are similar. For example, it is easier to compare a thermocouple with another thermocouple rather than with a resistance thermometer. This is true because the thermal response and output sensitivity of the test and standard thermometers are more nearly the same. For this reason, lower level standard thermometers are used in addition to platinum resistance thermometers.

Freezing point standards are used to calibrate reference standard thermocouples in the range 630 to 1063°C. These standards are high purity metal samples contained in graphite crucibles. A well is provided in the crucible into which the thermocouple measuring junction is inserted. The crucible is housed in a controlled muffle furnace. In use, the temperature of the sample is raised to a few degrees above the melting point and the furnace heat input to it reduced. The thermocouple is then inserted and its emf monitored as the crucible cools slowly. At the freezing temperature of the sample, the emf output of the thermocouple ceases to change. A stable plateau temperature is then maintained for a period of 15 to 30 min. In fact, the stability of the plateau is a measure of the purity of the sample.

There are four units, tin (232°C), zinc (420°C), aluminum (660°C), and copper (1083°C). Though these are not the defining points for the IPTS, their use does not introduce additional errors exceeding 0.2 deg.

The freezing temperatures of these samples have been cross-checked with an NBS calibrated thermocouple.

For temperatures above 1063°C, the instrument used to realize the IPTS is the optical pyrometer. This instrument is similar to a telescope, the main difference being that the filament of a small lamp is located at the focus of the objective lens in place of cross hairs. A battery is wired in series with the lamp filament. A means of controlling and measuring filament current is provided. In use, the instrument is focused on the object whose temperature is being measured. The apparent brightness of the filament is then varied until it matches the brightness of the object and seems to disappear.

The optical pyrometer is used to calibrate a tungsten strip lamp and pyrometric furnace. These items of equipment are then used for the calibration of other high temperature measuring devices.

Not shown on the chart are several devices required to establish the proper temperature environment in which test thermometers are calibrated. These include stirred baths, furances, and a cryogenic chamber. There are no calibration requirements for these devices. However, they must provide stable temperatures.

The Output of a Thermocouple is Measured at the Freezing Point of a Pure Metal.

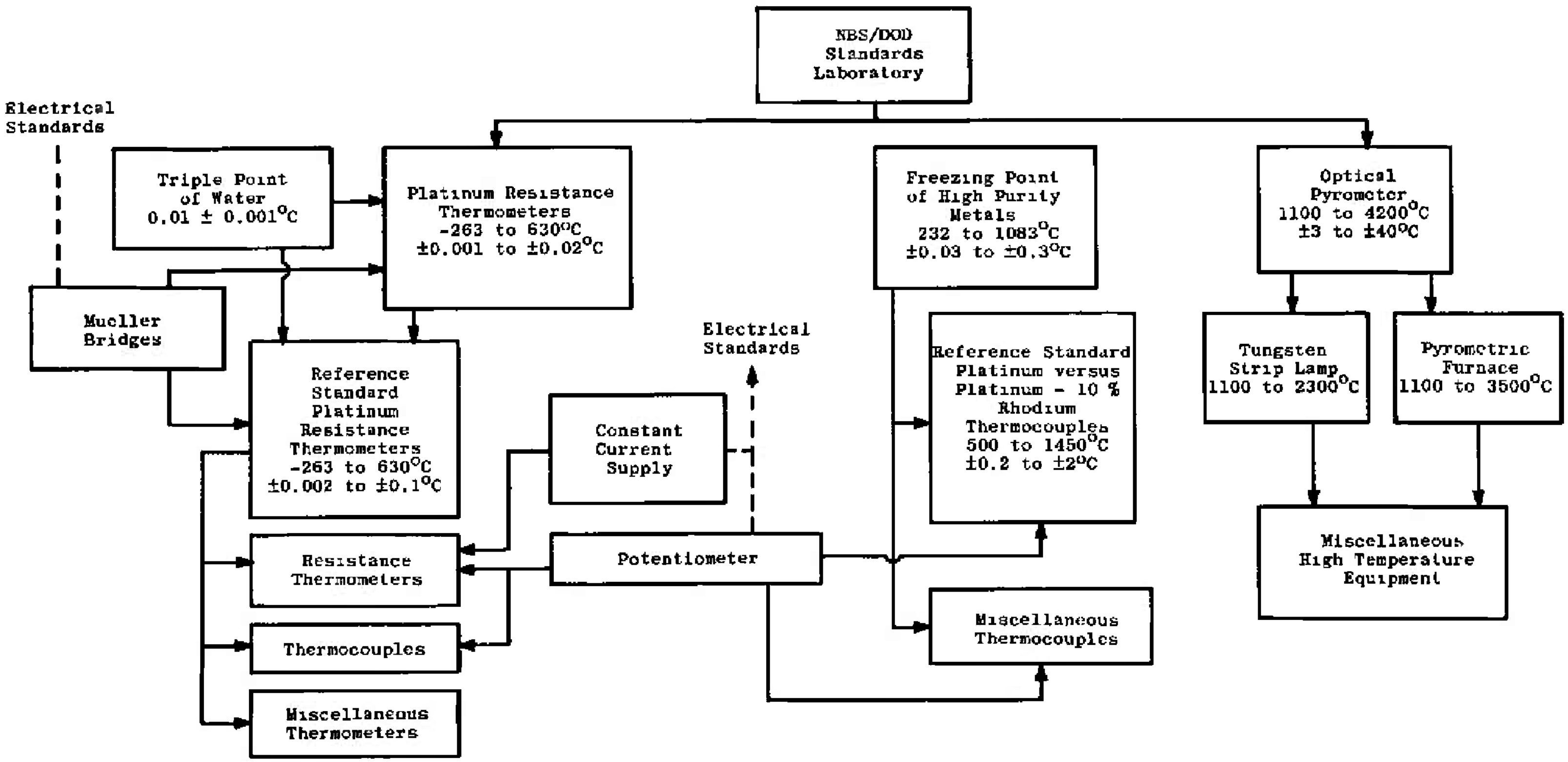


Fig. 3 Basic Temperature Measurements Capability and Traceability Chart

SECTION VI
MASS AND FORCE MEASUREMENTS

Mass is another of the fundamental units of our system of measurements. It is also used in the derivation of other units such as force, pressure, etc. Mass is defined as the quantity of matter in a body. It is a measure of its inertial property. If a body remains intact, its mass remains unchanged regardless of its location. The standard of mass for this country is the United States Prototype Kilogram 20. This standard is a 39- by 39-mm cylinder of platinum/iridium kept at the National Bureau of Standards in Washington, D. C. The mass of the standard is known in terms of the International Prototype Kilogram which is kept at the International Bureau of Weights and Measures at Sevres, France. The stability of the U. S. Prototype Kilogram 20 has been such that when recompared with the International Prototype Kilogram after 60 years, a change of only one part in 50 billion was found.

Two masses, regardless of their location, exert forces tending to bring them together. The forces that exist between two masses are proportional to the product of the two masses and inversely proportional to the square of the distance between the centers of gravity of the two masses. The attractive force that causes a mass out of contact with or unsupported by other bodies to fall to the earth is often called gravity or earthpull. The earthpull is a force just as real as other forces, that of a compressed spring for example. Weight is the term usually used to express the earthpull on a body. The earth attracts bodies of large mass with greater force than it attracts bodies of lesser mass. Thus when we lift various masses we are able to say whether one body is heavier than another.

Some confusion exists in this country concerning the concepts of mass and force because of common usage of the terms kilogram (kg), gram (gm), pound (lb), etc., for mass and force. The International Conference on Weights and Measures has defined the International Kilogram as a standard of mass. Other standard units of mass are derived from it and should be treated as such. For example, one pound (avoirdupois) is defined as 0.45359237 kg.

Common practice has also permitted use of the terms, kilogram, gram, pound, etc., when speaking of the weights of these standards. Mass standards ("weights") are usually calibrated and used on an equal arm balance. The effects of variation in the acceleration of gravity are self-eliminating and need not be taken into account. Therefore, two bodies of equal mass will be affected equally by any change in the value

of the acceleration of gravity, g. They have the same weight, and if they balance each other on an equal arm balance for one value of g, they will balance each other for other values of g, that is, at other locations.

This is not true of a spring balance. The weight of a body is balanced against the restoring force of a spring. The weight of a body would be found to change if the body and spring balance were moved to another locality with a different g.

As stated above, the weight of a body is the earthpull or gravitational force exerted on the body by the earth. Since the acceleration of a falling body is produced by the weight of the body, Newton's second law can be expressed in equation form for the weight of a body of mass m,

$$W = mg$$

with appropriate units. It is the common practice of using mass and force units interchangeably that results in some ambiguity when precise and accurate measurements are required.

An elementary review of units and definitions follows to clarify calibration results received.

The unit of force is the Newton and is defined as that force which imparts an acceleration of 1 m/sec/sec to a mass of 1 kg. This is called an absolute system because the units are defined in a manner that does not refer to the magnitude of g. For example, the weight of a 1-kg mass at the AEDC is 9.79657 Newtons.

If consideration is now given to gravitational force units, another system is introduced, which is not absolute. The kilogram-force is defined as the weight of a 1-kg mass at a specified location near the earth's surface where the acceleration of gravity has the standard value, g_s. The International Committee on Weights and Measures adopted the value of 980.665 cm/sec/sec as the value of g_s in 1901. This value corresponds closely with the value of g at latitude 45 deg and sea level. Thus, the weight of a 1-kg mass at this location is 9.80665 Newtons, and we see that 1-kg force is equal to 9.80665 Newtons.

There is in existence another absolute unit of force in the British FPS (foot, pound, second) system. This force unit is the poundal and is defined as the force required to give a mass of 1 lb an acceleration of 1 ft/sec/sec. This force unit is inconveniently small and is not widely used.

In engineering work, a British gravitational unit is generally used. The unit of force, the pound force (lb_f) is defined as the weight of a 1-lb mass at a place where the acceleration of gravity has the value g_s. The corresponding value of g_s is 32.17405 ft/sec/sec. From this definition of force, a mass unit, the slug, is defined. A slug is the mass to which a pound force will give an acceleration of 1 ft/sec/sec. This system appears rather involved since a new mass unit was defined in terms of a force unit. The force unit (lb_f) was itself defined in terms of the gravitational force exerted on a mass of 1 lb. However, it is worthwhile, because it permits the use of a force unit of convenient size. The magnitude of the slug can be seen to be more massive than the pound mass from Newton's law,

$$1\ lb_f = 1\ \text{slug ft/sec}^2$$

or

$$1\ \text{slug} = 32.17405\ \text{lb mass}$$

When the above absolute and gravitational systems are used, the procedure is straightforward. The usual confusion exists because the pound is used as a mass unit and a force unit. This can be done provided the definition of the pound force is used and Newton's second law written accordingly. The pound force was defined above and the mass unit (slug) defined to numerically balance the equation. To use the pound for both force and mass, Newton's law requires the introduction of a dimensionless constant, g_o, as follows:

$$g_o W = mg$$

Here W is the weight or force in lb_f, m is the mass in pounds, and g is local gravity in feet per second per second. The value of g_o is the same numerically as g_s, standard gravity.

An examination of the above equation will show that numerically the weight or force of a 1-lb mass is equal to the ratio of local g to g_s. This is a little difficult to analyze dimensionally, but if the definition of the lb_f is considered then the weight at any locality is simply that proportional part of the defined lb_f unit caused by a change from standard to local g.

The value of g has been determined at this locality and found to be 979.657 cm/sec^2. The weight or force of a 1-lb mass at the AEDC is then 0.998972 lb_f.

For very precise and accurate measurements using standards of mass, the buoyancy or lifting effect of air must be considered. This results from application of Archimedes' principle. Two bodies of

equal mass will balance each other on an equal arm balance in a vacuum. A comparison in a vacuum against a known mass standard gives true mass. However, if the comparison were made in air, they would not balance each other unless the volumes were equal. The greater the difference in volume, and the greater the density of air in which the comparison is made, the greater will be the apparent difference in weight. In assigning a precise numerical value to a standard mass, it is necessary to know the conditions under which the comparison was made. When mass comparisons are made in this branch, the values given are apparent mass versus normal brass standards at the conditions given on the report. If absolute values are required, these can be calculated using the equation

$$M_x = M_s + P_a M_s \left(\frac{1}{P_x} - \frac{1}{P_s}\right)$$

where

M_x = mass of the weight tested

M_s = mass of the standard

P_a = density of the air

P_x = density of the weight tested

P_s = density of the standard

Normal brass standards are defined as having a density of 8.4 gm/cc at 0°C and a cubical thermal expansion coefficient of 0.000054/°C.

Weights are classified according to their intended use. NBS Circular 547, Section 1, gives information on the classes, construction, and tolerances, etc., of standards of mass and laboratory weights.

Density is defined as the mass per unit volume and is usually expressed in grams per cubic centimeter at some temperature. This property of liquids is of importance, for example, when using liquid columns for pressure determinations. Since determination of the density of a liquid is a type of weighing (hydrostatic), it is included in this section.

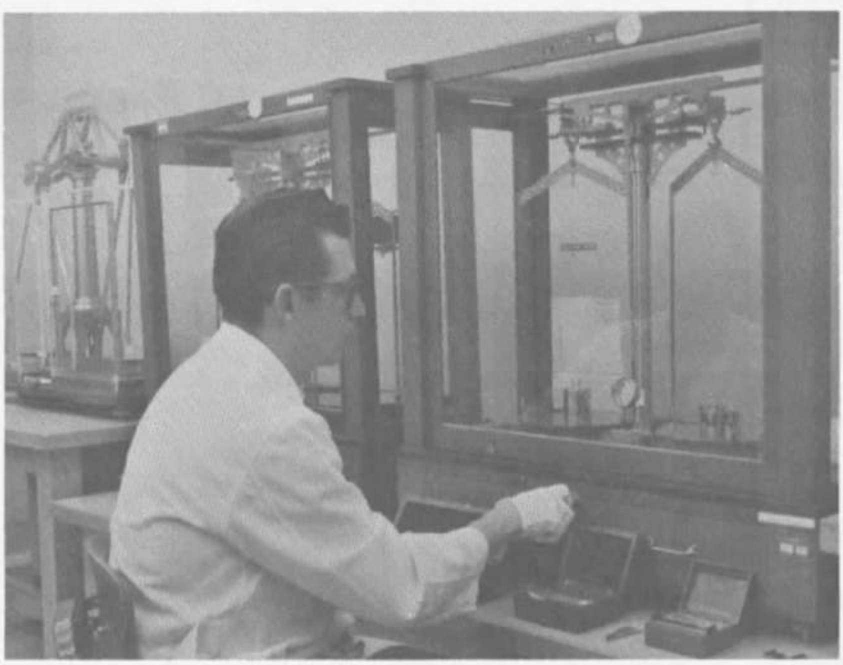
Specific gravity is a dimensionless number expressing the ratio of the weight of a fixed volume of liquid to the weight of the same volume of another substance taken as a standard at a stated temperature. Care must be exercised in stating the reference temperature and liquid used; otherwise there is danger of misinterpretation of results.

Specific gravity of a liquid may be determined at any convenient temperature and referenced to water at any desired temperature.

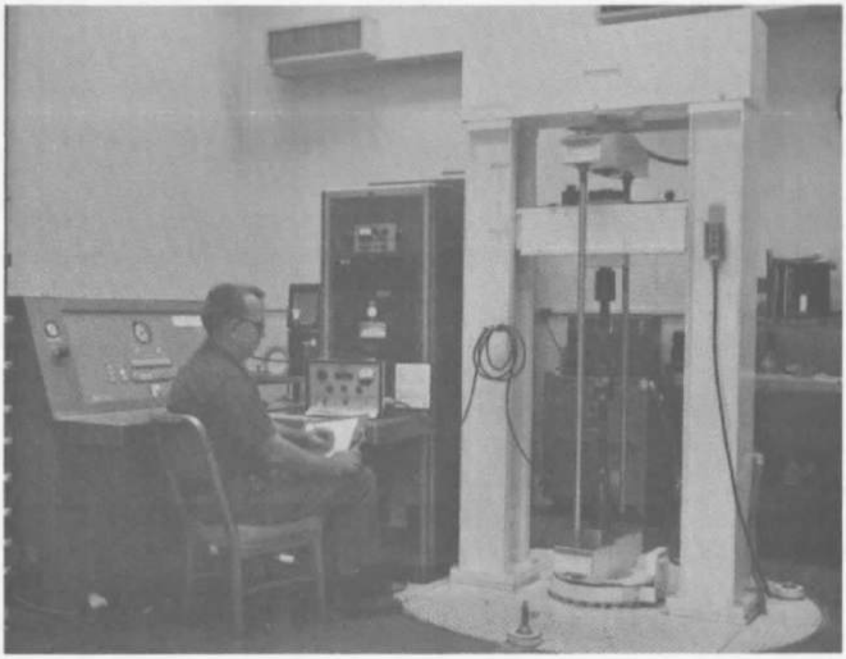
Consider, for example, the specific gravity of a liquid determined at 20°C. It is usually written as 20°/20°C, 20°/4°C, etc., to denote that it is referred to water at 20°C and 4°C, etc. The preferable method, and that used in this branch, is to state specific gravity in terms of water at 4°C. Values are then directly comparable since they are measured in terms of the same unit. Also, when specific gravities are so expressed, they are numerically the same as densities in grams per milliliter. Although density in the metric system is expressed in grams per cubic centimeter, the above is sufficient for ordinary determinations as one milliliter is equal to 1.000028 cm^3.

The Mass and Force Measurements Capability and Traceability Chart is shown in Fig. 4, page 31. The units of mass are preserved by a group of interlaboratory standard weight ranging in size from 1 mg to 25 kg. Their function is that of transferring known values of mass from a recognized higher level laboratory to the AEDC.

These interlaboratory weights are used for adjusting the equal arm balances and determining their sensitivity. These balances cover various ranges up to 100 Kg. The appropriate balance and interlaboratory weights are then used for determining the mass of the reference weights, which are in turn used for day-to-day weighings of laboratory and test weights received for calibration.



Intercomparison of Interlaboratory and Reference Mass Standards



30,000-lb Deadweight Calibrator
(Weights are Located under the Yoke)

The specific gravity of liquids is determined on a routing basis using a specially constructed balance graduated in specific gravity values referred to water at 4°C. This unit covers the range of specific gravities up to two. It is periodically checked against a sample of triple distilled water at various temperatures. For more precise work, a hand-lapped invar plummet and equal arm balance are used. The specific gravity of liquids is calculated from the loss of weight of the plummet when immersed in the liquid.

The calibration of force measuring devices is accomplished by the chain of measurements shown in Fig. 4. The equipment and methods used depend upon the magnitude of the forces applied.

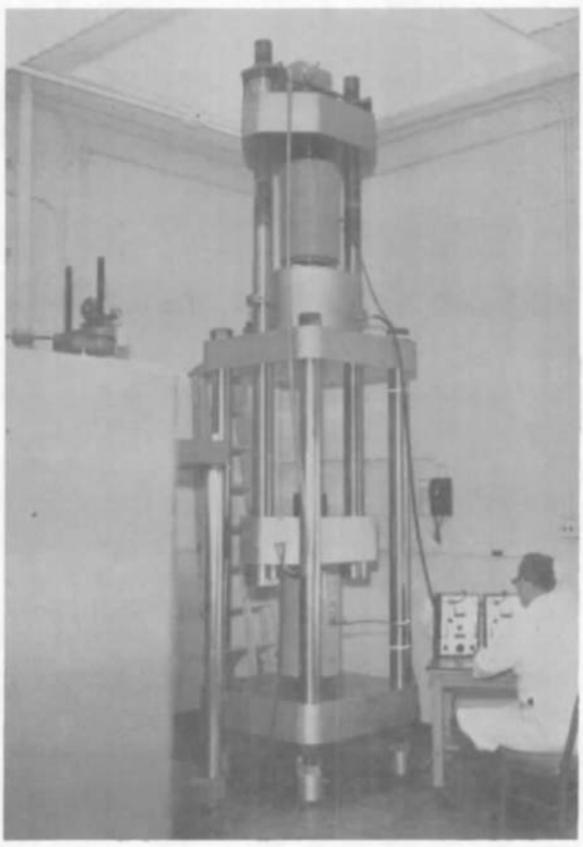
For forces up to 500 lb, a group of assorted weights up to 50 lb is used. These weights are calibrated on an equal arm balancc by comparison with referencc mass standards. These mass values are then converted to true force units. These weights are sequcntially loaded on a hanger device by a hydraulic ram.

For loads up to 30, 000 lb, a commercially available deadweight calibrator was purchased. The smallest value that can be applied is 400 lb. This is caused by the weight of the yoke required for holding the devices being calibrated. The construction of the calibrator is

such that the weights are either suspended or removed from a pull rod by pneumatic bellows. The weight values are sized to permit calibration in approximately 20-percent increments of full-scale ranges from 2000 to 30, 000 lb. These weights were adjusted to Class "C" tolerances by the NBS Master Scale Depot in Chicago, Illinois.

A series of transfer standards is available for use where it is not feasible to send a device to the laboratory for calibration. These units are calibrated on the deadweight calibrator. The value of 120, 000 lb is achieved by calibrating four load cells in series and then loading them in parallel. The 500, 000-lb load cell is calibrated with deadweights by NASA at MFSC. The load cell is used in a hydraulic press for the calibration of comparable load cells.

Most force measuring devices calibrated use some type of circuitry wherein an electrical input voltage is applied and the output voltage is proportional to the applied load. The readout devices used are periodically calibrated against the electrical standards shown in Fig. 1.



Two 500,000-lb Load Cells are Compared Using an Hydraulic Calibrator.

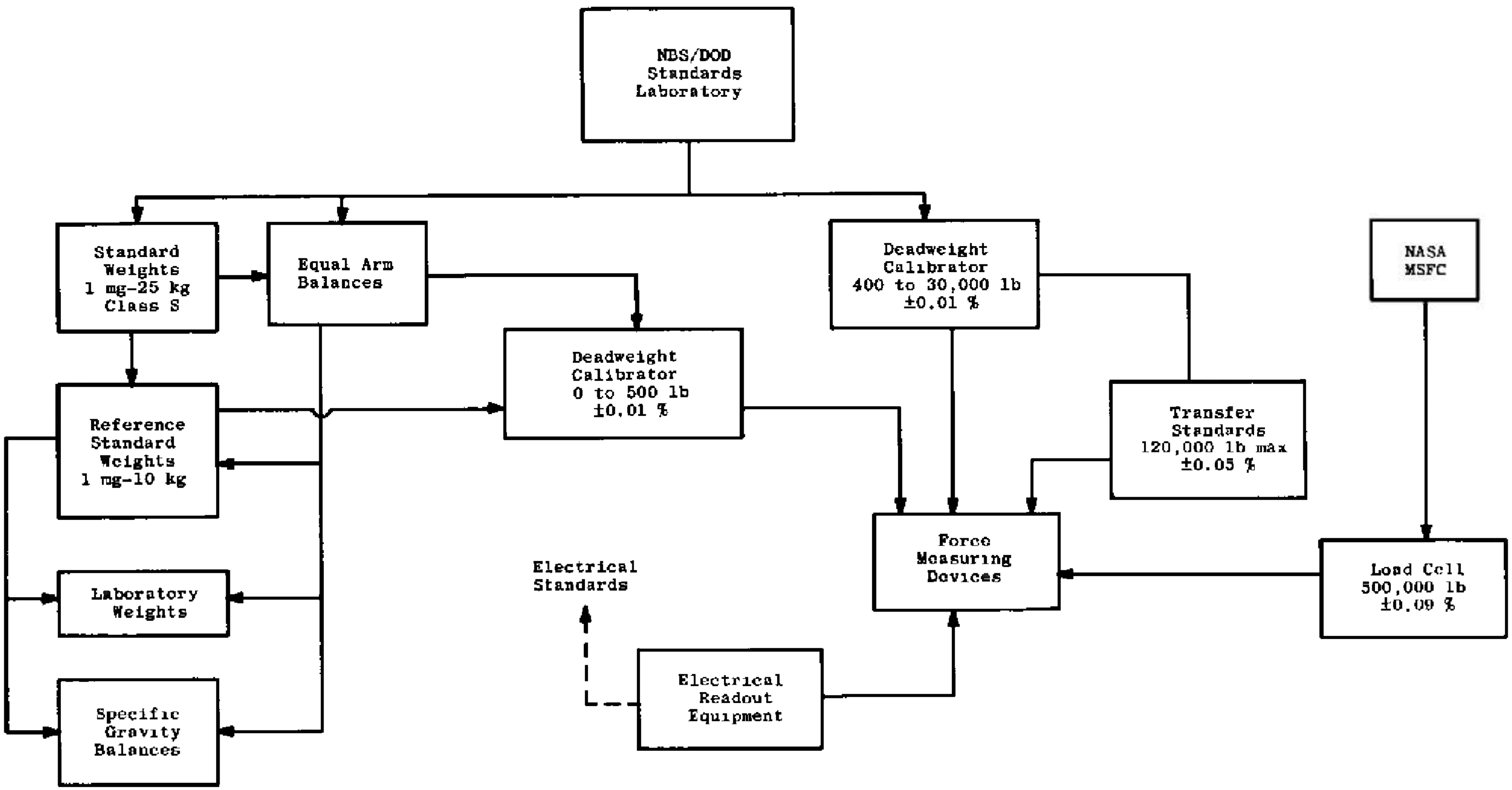


Fig. 4 Mass and Force Measurements Capability and Traceability Chart

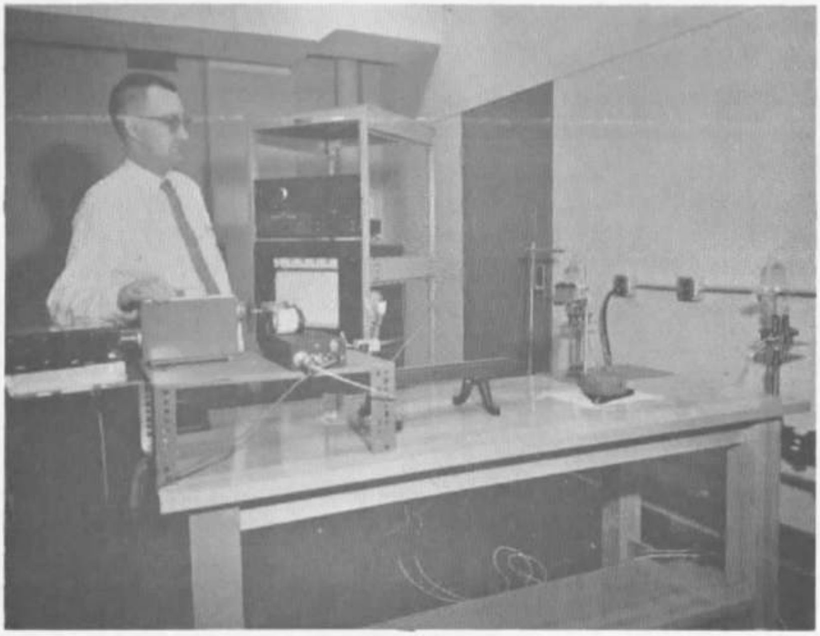
SECTION VII
RADIOMETRY AND PHOTOMETRY MEASUREMENTS

Radiation is generally understood to mean the transfer of energy by either emitted waves or particles. Radiant energy is the type of energy emitted in the form of electromagnetic waves. For this discussion, it will be limited to radiant energy or radiation which is emitted from some material substance excited by heat or electrical discharge.

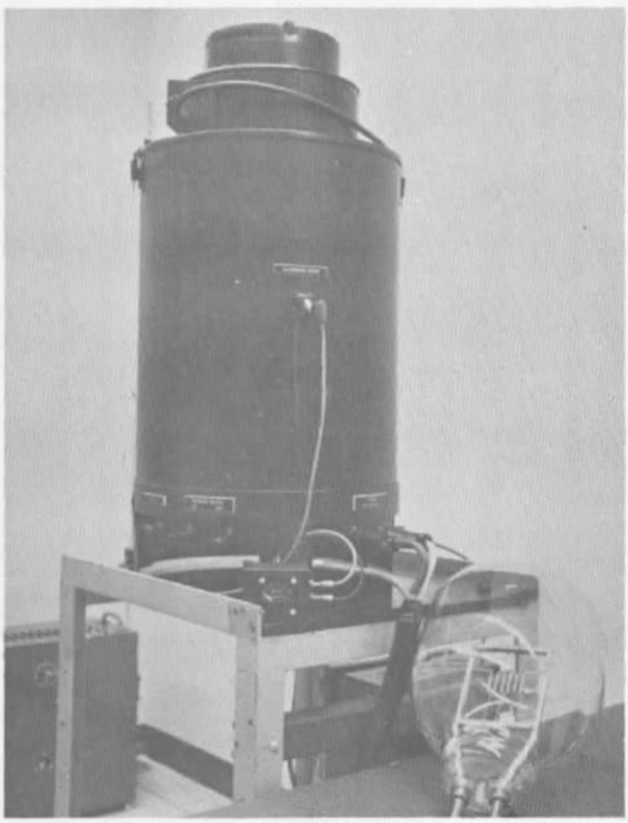
The first standards used to evaluate radiant energy were the oil lamp and candle. With the introduction of the blackbody, it was soon recognized that total and spectral radiation characteristics can be defined in terms of Planck's radiation law. The setting up and operation of a blackbody is a long and tedious operation that few laboratories are equipped to perform. The NBS has a program for developing and making available to calibration laboratories lamps suitable for use as radiation standards. The calibration of these standards is based upon the radiation from a blackbody.

In the physics of radiation, it is well to define terms used so that calibration results may be properly utilized. The radiant energy which is emitted by a source per unit of time or which strikes or crosses a surface per unit of time is called radiant flux. The radiant flux incident on a surface per unit area is designated irradiance. Since radiant flux is a flow of energy, it can be expressed in units of power or energy per unit of time that is incident upon a unit area. The irradiance from the sun, usually referred to as one solar constant, is generally given as the energy that falls in one minute upon a square centimeter at the earth's mean distance and normal to the sun's rays, is approximately 2 cal/cm^2 min (140 mw/cm^2). This is known as total irradiance, i.e., for all wavelengths. Another type of measurement known as spectral irradiance is a measure of the radiant flux at a particular wavelength for a given wavelength interval. For example, the spectral irradiance at a particular wavelength can be expressed in units of mw/cm^2-nm. This gives the time rate of energy (mw) incident on unit area (cm^2) contained in a wavelength interval of one nanometer (mμ) at the specified wavelength. Standards for these measurements usually give the irradiance at a specified distance and the limitations on calculating values at other distances.

Another measurement known as spectral radiance is the radiant flux per unit solid angle per unit area of source, per wavelength interval at a specified wavelength. For example, at a specified wavelength, spectral radiance would have the form μw/steradian-nanometer-mm^2 of source.



The Substitution Method is Used for Comparison of Spectral Radiance Standards.

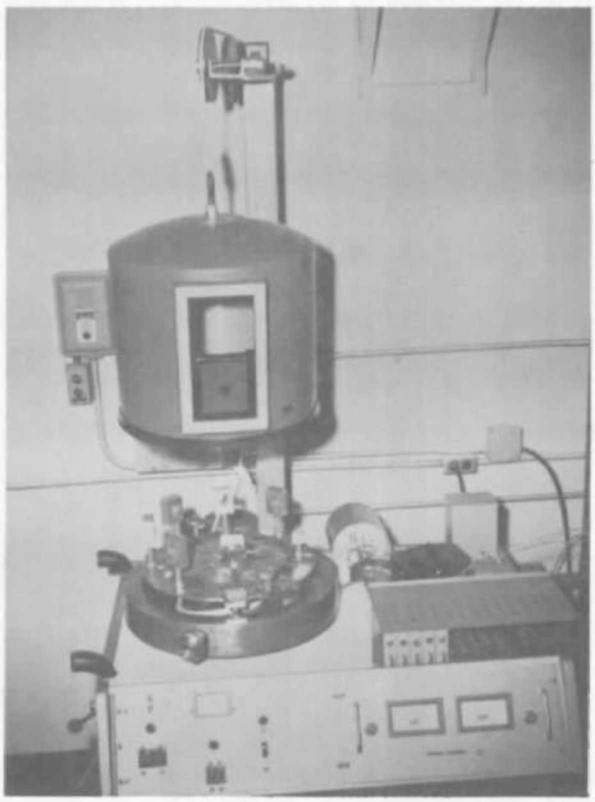


With This Lamp and Water-Cooled Housing, Total Irradiance Up to Three Solar Constants May Be Obtained

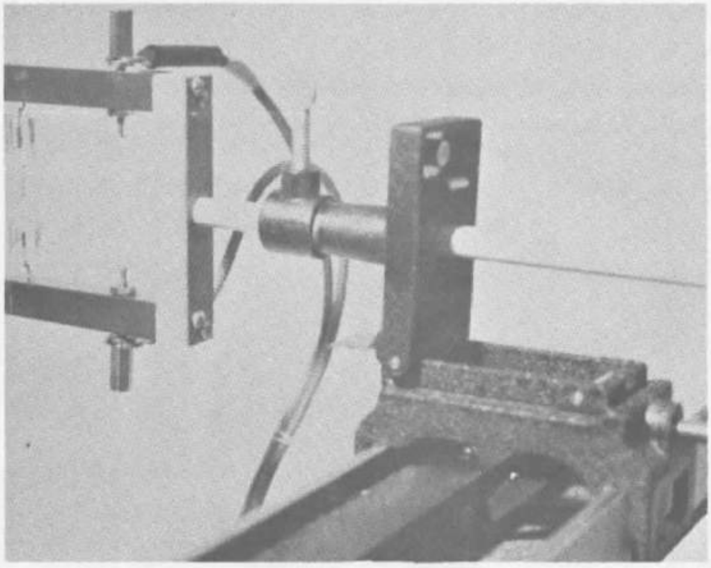
The above discussion of radiant flux was purely objective or from the physical standpoint. Photometry is that part of radiometry which deals with radiant flux evaluated in terms of the visual sensations produced. One of these visual sensations is brightness, which may be defined as that property of any color sensation which permits it to be classified as equivalent to the sensation produced by one of a series of neutral grays. Radiant flux evaluated according to its ability to evoke the sensation of brightness is called luminous flux. The unit of luminous flux is the lumen. The luminous intensity of a source is flux emitted per unit solid angle. The unit of intensity is one lumen per steradian and is called a candela.

When luminous flux strikes a surface it can be said that the surface is illuminated. Analogous to the term irradiance is a quantity known as illuminance. This quantity is luminous flux incident per unit area. A lux is defined as one lumen/meter^2 and a foot candle is defined as one lumen/foot^2.

A standard of luminous intensity can be used with some comparison device such as a photometer to determine the luminous intensity of other sources. Also, the illuminance from the standard may be calculated for that particular distance.



Equipment Used for the Calibration of Total Radiation Detectors under Vacuum



Quartz Iodine Lamp Used as a
Standard of Spectral Irradiance

The basic capability and traceability chart for radiometry and photometry measurements is shown in Fig. 5, page 37. The standard of spectral radiance is a tungsten strip lamp with quartz window. The lamp used for spectral irradiance measurements has a tungsten-coiled-coil filament enclosed in a small quartz envelope containing a small amount of iodine. A grating monochromator, not shown on the chart, is used for separation of the energy into various wavelengths. Duplicate lamps are used for interlaboratory and reference standards. The radiance from the lamps changes with hours of usage. For this reason, it is particularly advantageous to use the interlaboratory standard only for calibration of the reference standard. In this way the useful life of the reference standard can be determined. The intercomparison of standards as well as the calibration of other lamps is by the direct substitution method. The standard and test lamps are placed in the same position. No knowledge of the auxiliary optics, spectral transmittance of the monochromator, or spectral sensitivity of the detector is required.

The standards for total irradiance are a small carbon filament lamp and a 5000-w tungsten coil filament lamp. In this case, only one standard is used. After a number of hours use, the lamp is no longer a reliable standard. The cost of the lamp is small compared with the cost of calibration. Also, the lamp must be aged before calibration. It is considered to be more economical to purchase a new calibrated standard when required. A detector that has been calibrated by a higher level laboratory is on hand for the calibration of total radiation detectors under certain conditions not readily obtainable with the standard source.

The standards of luminous intensity consist of two lamps to cover the range of values shown in Fig. 5. A photometer is used with these lamps for the calibration of other lamps. For the calibration of illumination meters, the illuminance is calculated by the inverse square law. Reference standards are purchased as required for the same reasons as noted above for total irradiance standards.

Calibration of Illuminotion Meters

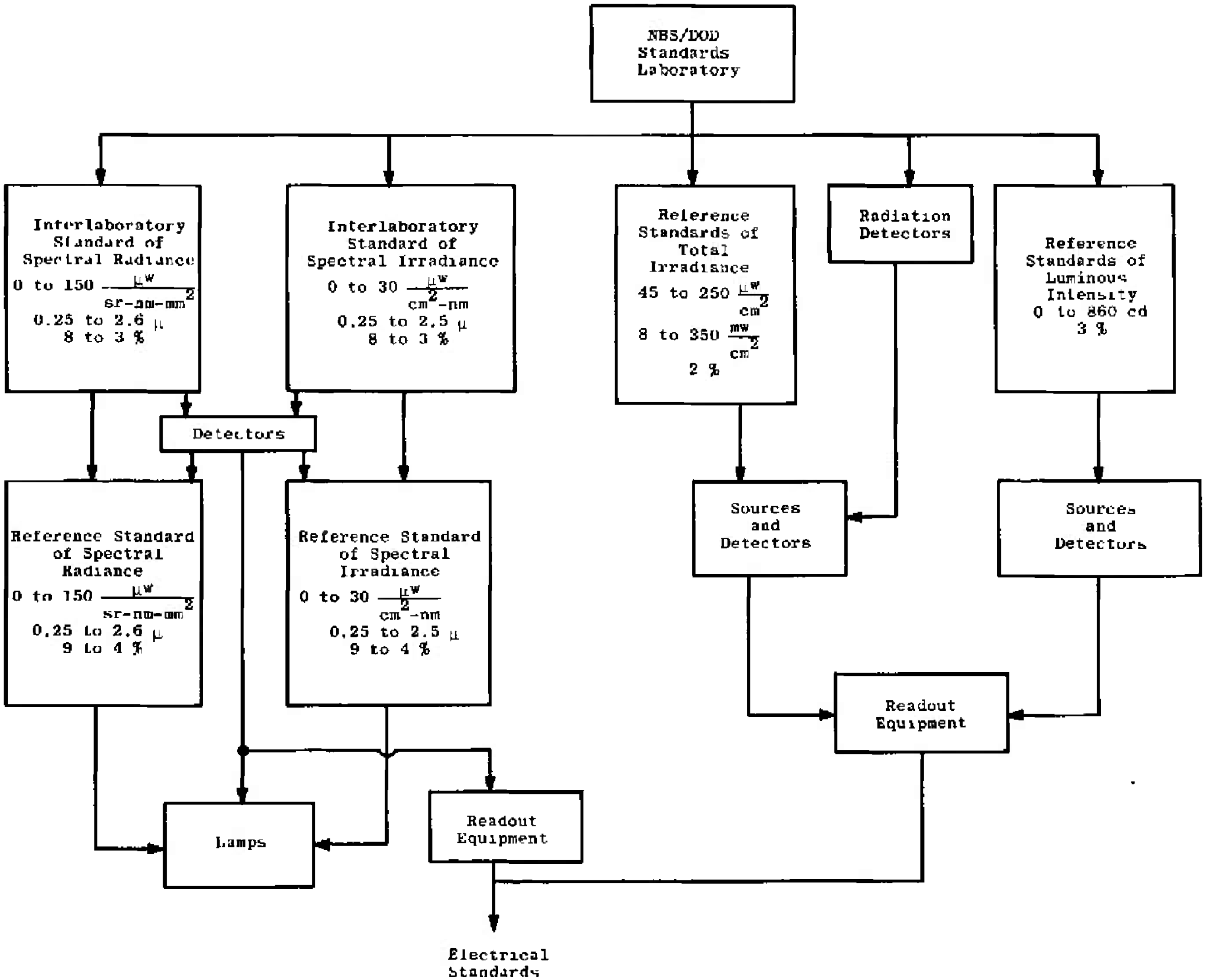


Fig. 5 Basic Radiometry and Photometry Measurements Capability and Traceability Chart

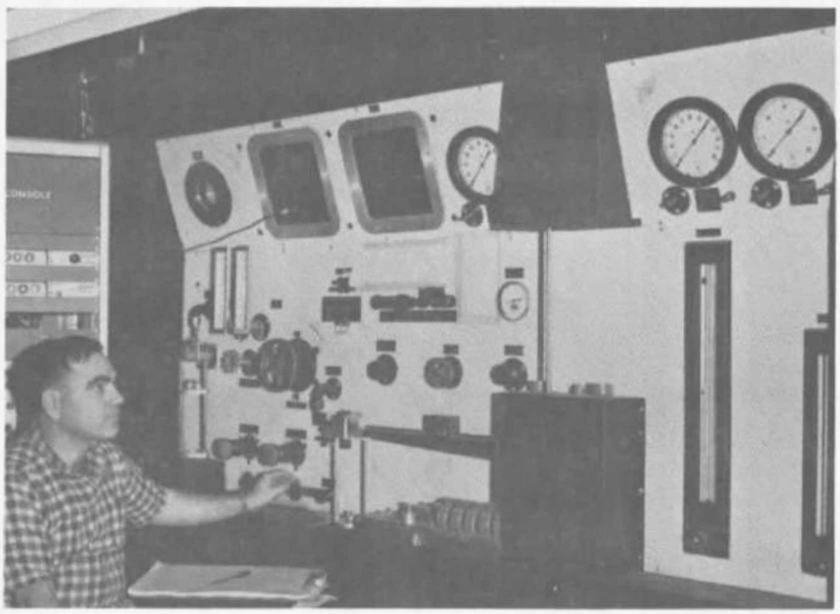
SECTION VIII
MISCELLANEOUS MEASUREMENTS

Some calibration services are provided that do not conveniently fit under classifications previously given. Information on these services is given below.

8.1 FLUID FLOW

The calibration of various types of liquid flowmeters is accomplished using a dynamic weigh-type flow bench. The equipment is a Cox Type 311 AHT flow calibrator particularly designed for the calibration of turbine-type flowmeters. Direct reading flowmeters are also accommodated.

The stand incorporates a high and a low flow system which are independent of each other. Water is used as the calibrating fluid. The low flow system covers the range from 0.014 to 2.8 gpm (5 to 1000 pph) and the high flow system covers the range 1.4 to 416 gpm (500 to 150,000 pph). Weighing cycles of 30 sec or more are used.



Flow Calibration Stand

The calibration of the stand is accomplished by checking individual components (timer, counter, weigh beam sensitivity, and lever ratio, etc.) against appropriate standards. The overall performance of the system is compared with transfer flowmeters to determine compatibility with NBS. The transfer standards consist of three flowmeters

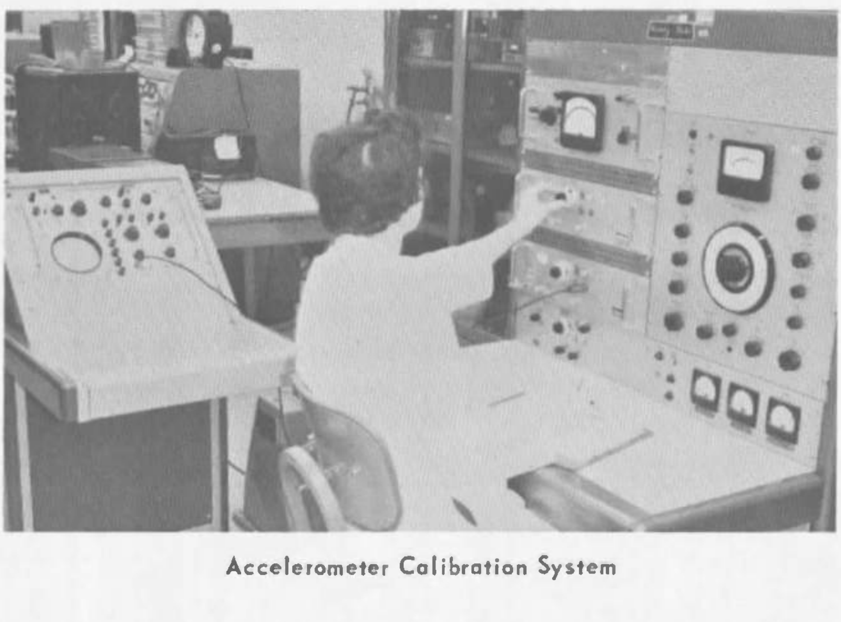
that were selected because of their repeatability. They were assembled in straightening vane configurations recommended by NBS. When these flowmeters were purchased, calibration data were received. The flowmeters were also sent to NBS for calibration. This has permitted a comparison of flow calibration data obtained locally with that of two other calibration laboratories. The accuracy estimates for the flow stand are 0.2 percent for flow rates up to 75 gpm and 0.25 percent for flowrates above 75 gpm.

For liquid flowrates above the range of the flow stand, as well as gas flowmeters, arrangements have been made with the Marshall Space Flight Center at Huntsville, Alabama, to obtain calibration services.

8.2 VIBRATION

A shaker system is used for the calibration of accelerometers and vibration pickups. The system was designed for rapid calibration of piezoelectric accelerometers. Acceleration levels are determined by a reference accelerometer contained in the shaker table. Test accelerometers are mounted back-to-back with the reference accelerometer. Calibration of the reference accelerometer is accomplished by using an interlaboratory standard sent to a higher level laboratory for calibration. Accuracies obtainable with this equipment do not exceed ±2.5 percent from 10 to 900 Hz and ±4.5 percent from 900 to 5000 Hz. The operating limits of the equipment are shown in Fig. 6, page 40.

Velocity calibrations are performed using the integrated output of the reference accelerometer. For displacement transducers, a telescope is used for determining the peak-to-peak values.



Accelerometer Calibration System

8.3 TORQUE

For the calibration of torque wrenches, a bench tester is used. This equipment was procured specifically for this purpose. The maximum capacity is 7500 lb-ft. It can also be used for the calibration of cable tensiometers up to 4000 lb.

In operation, a torque is applied at one of four testing stations. The force is transmitted to a master lever through the station lever and link which moves the master lever and in turn the pull rod attached to it. The pull rod deflects a beam through a lever system. The beam movement is transmitted to a dial gage by a spring-loaded rack assembly.

The calibration of the tester is accomplished by using special test bars and known weights at each station. Torque values correct to ±2 percent can be obtained.

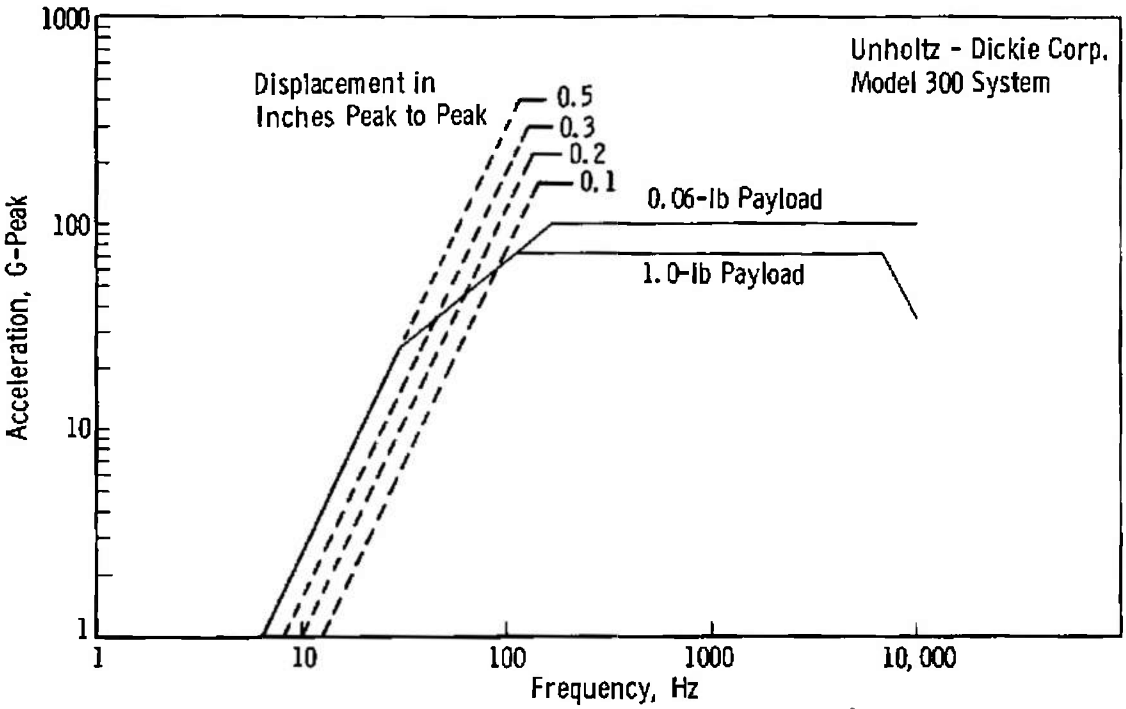


Fig. 6 Operational Limits - Model 300 Calibration System

SECTION IX
INTERNATIONAL SYSTEM OF UNITS

An International System of Units, the Systéme International d'Unités (international abbreviation SI), was defined and officially sanctioned by the representatives to the 1960 Eleventh General Conference on weights and measures.

In this country, the NBS announced in Administrative Bulletin 64-6 (February 1964) that "...Henceforth it shall be the policy of the National Bureau of Standards to use the units of the International System (SI), as adopted by the Eleventh General Conference on weights and measures..., except when the use of these units would obviously impair communication or reduce the usefulness of a report to the primary recipients."

Other organizations in this country - for example, some NASA field centers, have followed this lead. For this reason, some definitions and conversion factors are included as an aid to those groups having such a requirement. For a more complete discussion of the SI, the reader is referred to NASA SP-7012, The International System of Units, Physical Constants and Conversion Factors, by E. A. Mechtly from which this information was extracted.

The following prefixes are used to designate multiples and sub-multiples of units:

Multiplying Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

Six units have been adopted to serve as a practical base for a system of measures for international relations. These units and definitions are as follows:

1. The unit of length, meter (m), is the length of exactly 1, 650, 763. 73 wavelengths of the radiation in vacuum corresponding to the unperturbed transition between the levels $2p_{10}$ and $5d_5$ of the atom of Krypton 86, the orange-red line.

2. The unit of mass, kilogram (kg), is the mass of a cylinder of platinum-iridium alloy, designated the International Prototype Kilogram, which is preserved in a vault at Seyres, France, by the International Bureau of Weights and Measures.

3. The unit of time, ephemeris second (s), is exactly 1/31, 556, 925. 9747 of the tropical year of 1900, January, 0 days and 12 hr ephemeris time.

4. The unit of electric current, ampere (A), is the constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular sections, and placed one meter apart in a vacuum, will produce between these conductors a force equal to 2×10^{-7} newton per meter of length.

5. The thermodynamic Kelvin degree is the unit of temperature determined by the Carnot cycle with the triple-point temperature of water defined as exactly 273. 16°K.

The International Practical Kelvin and Celsius Temperature Scales of 1960 are defined by a set of interpolation equations based on the following reference temperatures:

	°K	°C
Oxygen, liquid-gas equilibrium	90. 18	-182. 97
Water, solid-liquid equilibrium	273. 15	0. 00
Water, solid-liquid-gas equilibrium	273. 16	0. 01
Water, liquid-gas equilibrium	373. 15	100. 00
Zinc, solid-liquid equilibrium	692. 655	419. 505
Sulphur, liquid-gas equilibrium	717. 75	444. 6
Silver, solid-liquid equilibrium	1233. 95	960. 8
Gold, solid-liquid equilibrium	1336. 15	1063. 0

6. The unit of luminous intensity, candela (cd), is of such value that the luminous intensity of a full radiator at the freezing temperature of platinum is 60 candela per centimeter squared.

The following units will be used in the SI without prejudice to other units which could be added in the future.

Supplementary Units

Plane angle	radian	rad
Solid angle	steradian	sr

Derived Units

Area	square meter	m^2	
Volume	cubic meter	m^3	
Frequency	hertz	Hz	(S^{-1})
Density	kilogram per cubic meter	kg/m^3	
Velocity	meter per second	m/s	
Angular velocity	radian per second	rad/s	
Acceleration	meter per second squared	m/s^2	
Angular acceleration	radian per second squared	rad/s^2	
Force	newton	N	$(kg.m/s^2)$
Pressure	newton per square meter	N/m^2	
Kinematic viscosity	square meter per second	m^2/s	
Dynamic viscosity	newton-second per square meter	$N\text{-}s/m^2$	
Work, energy, quantity of heat	joule	J	$(N \cdot m)$
power	watt	W	(J/s)
Electric charge	Coulomb	C	(A.s.)
Voltage, potential difference, electromotive force	volt	V	(W/A)
Electric field strength	volt per meter	V/m	
Electric resistance	ohm	Ω	(V/A)
Electric capacitance	farad	F	$(A \cdot s/V)$
Magnetic flux	weber	wb	$(V \cdot s)$
Inductance	henry	H	(V.s/A)
Magnetic flux density	tesla	T	(Wb/m^2)
Magnetic field strength	ampere per meter	A/m	
Magnetomotive force	ampere	A	
Luminous flux	lumen	lm	(cd. sr)
Luminance	candela per square meter	cd/m^2	
Illumination	lux	lx	(lm/m^2)

The conversion factors listed below provide multiplying factors for converting measurements given by numbers and miscellaneous units to corresponding new numbers and SI units listed by physical quantity.

To convert from	To	Multiply by
	Acceleration	
feet/second^2	meter/second^2	3.048×10^{-1}
centimeters/second^2	meters/second^2	1.00×10^{-2}
inches/second^2	meters/second^2	2.54×10^{-2}
	Area	
acre	meter^2	$4.0468564224 \times 10^{3}$
circular mil	meter^2	$5.0670748 \times 10^{-10}$
foot^2	meter^2	9.290304×10^{-2}
inch^2	meter^2	6.4516×10^{-4}
mile^2 (U.S. Statue)	meter^2	$2.589988110336 \times 10^{6}$
	Density	
gram/centimeter^3	kilogram/meter^3	1.00×10^{3}
lbm/inch^3	kilogram/meter^3	2.7679905×10^{4}
lbm/foot^3	kilogram/meter^3	1.6018463×10
slug/foot^3	kilogram/meter^3	5.15379×10^{2}
	Electrical	
abampere	ampere	1.00×10
ampere (international of 1948)	ampere	9.99835×10^{-1}
statampere	ampere	3.335640×10^{-10}
gilbert	ampere turn	7.9577472×10^{-1}
oersted	ampere/meter	7.9577472×10
abcoulomb	coulomb	1.00×10
coulomb (international of 1948)	coulomb	9.99835×10^{-1}
faraday (chemical)	coulomb	9.64957×10^{4}
farady (physical)	coulomb	9.65219×10^{4}

farad (international of 1948)	farad	9.99505×10^{-1}
henry (international of 1948)	henry	1.000495
ohm (international of 1948)	ohm	1.000495
gauss	tesla	1.00×10^{-4}
volt (international of 1948)	volt	1.000330
maxwell	weber	1.00×10^{-8}
unit pole	weber	1.256637×10^{-7}

Energy

BTU (International Steam Table)	joule	1.05504×10^{3}
BTU (mean)	joule	1.05587×10^{3}
BTU (39°F)	joule	1.05967×10^{3}
BTU (60°F)	joule	1.05468×10^{3}
calorie (International Steam Table)	joule	4.1868
calorie (mean)	joule	4.19002
calorie (15°C)	joule	4.18580
calorie (20°C)	joule	4.18190
electron volt	joule	1.60210×10^{-19}
erg	joule	1.00×10^{-7}
foot lbf	joule	1.3558179
foot poundal	joule	4.2140110×10^{-2}
joule (International of 1948)	joule	1.000165
watt hour	joule	3.60×10^{3}

Force

dyne	newton	1.00×10^{-5}
kilogram force	newton	9.80665

pound force (avoirdupois)	newton	4.4482216152605
poundal	newton	$1.38254954376 \times 10^{-1}$
	Frequency	
cycle per second	hertz	1.00
	Length	
Angstrom	meter	10^{-10}
foot	meter	3.048×10^{-1}
inch	meter	2.54×10^{-2}
meter	wavelength Kr 86	1.65076373×10^{6}
micron	meter	1.00×10^{-6}
mil	meter	2.54×10^{-5}
mile (U.S. Statute)	meter	1.609344×10^{3}
mile (U.S. nautical)	meter	1.852×10^{3}
yard	meter	9.144×10^{-1}
	Mass	
gram	kilogram	1.00×10^{-3}
pound mass (avoirdupois)	kilogram	4.5359237×10^{-1}
ounce mass (avoirdupois)	kilogram	$2.8349523125 \times 10^{-2}$
slug	kilogram	1.45939029×10
	Power	
foot lbf/minute	watt	2.2596966×10^{-2}
horsepower (550 foot lbf/sec)	watt	7.4569987×10^{2}
horsepower (boiler)	watt	9.80950×10^{3}
horsepower (electric)	watt	7.46×10^{2}
watt (international of 1948)	watt	1.000165

	Pressure	
atmosphere	newton/meter^2	1.01325×10^5
bar	newton/meter^2	1.00×10^5
cm Hg (0°C)	newton/meter^2	1.33322×10^3
cm H_2O (4°C)	newton/meter^2	9.80638×10
dyne/cm^2	newton/meter^2	1.00×10^{-1}
foot of water (39.2°F)	newton/meter^2	2.98898×10^3
inch of Hg (32°F)	newton/meter^2	3.386389×10^3
inch of Hg (60°F)	newton/meter^2	3.37685×10^3
inch of water (60°F)	newton/meter^2	2.4884×10^2
lbf/foot^2 (psf)	newton/meter^2	4.7880258×10
lbf/inch^2 (psi)	newton/meter^2	6.8947572×10^3
torr (0°C)	newton/meter^2	1.33322×10^2
	Speed	
feet/second	meter/second	3.048×10^{-1}
inch/second	meter/second	2.54×10^{-2}
knot (international)	meter/second	5.144444×10^{-1}
	Temperature	
degrees Celsius (C)	degrees Kelvin (K)	K = C + 273.15
degrees Fahrenheit (F)	degrees Kelvin (K)	K = (5/9) (F + 459.67)
degrees Rankine (R)	degrees Kelvin (K)	K = 5/9 R
degrees Fahrenheit (F)	degrees Celsius (C)	C = (5/9) (F-32)
degrees Kelvin (K)	degrees Celsius (C)	C = K-273.15
	Viscosity	
centistoke	meter^2/second	1.00×10^{-6}
centipoise	newton second/meter^2	1.00×10^{-3}
lb mass/foot second	newton second/meter^2	1.4881639
lb force second/foot^2	newton second/meter^2	4.7880258×10
	Volume	
foot^3	meter^3	$2.8316846592 \times 10^{-2}$
gallon (U.S. liquid)	meter^3	$3.785411784 \times 10^{-3}$

$inch^3$	$meter^3$	1.6387064×10^{-5}
liter	$meter^3$	1.00×10^{-3}
pint (U.S. liquid)	$meter^3$	$4.73176473 \times 10^{-4}$
$yard^3$	$meter^3$	$7.64554857984 \times 10^{-1}$
	Miscellaneous	
degree (angle)	radian	$1.7453292519943 \times 10^{-2}$
$foot^3$/second	$meter^3$/second	$2.8316846592 \times 10^{-2}$
BTU (thermochemical) lbm °F	joule/kg °C	4.184×10^3
rad (radiation dose absorbed)	joule/kg	1.00×10^{-2}
roentgen	coulomb/kg	2.57976×10^{-4}
Curie	disintegration/sec	3.7×10^{10}
Btu inch/$foot^2$ second °F	joule/meter sec °K	5.1887315×10^2
day (mean solar)	second (mean solar)	8.64×10^4
day (sideral)	second (mean solar)	8.6164090×10^4
year (calendar)	second (mean solar)	3.1536×10^7
year (sideral)	second (mean solar)	3.1558150×10^7

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13 ABSTRACT

To gather the required performance test data at the AEDC, a complex network of test instrumentation and data gathering equipment must operate as a system. Reliable test data depend upon the reliability of each individual unit of the system; therefore, known standards must be established to meet specific requirements. In addition, various research groups are engaged in special projects often requiring some accuracy level in the measurement of physical variables. In today's technology of the space age, pressure is continuously exerted to obtain greater performance from all systems. Increased performance of complex systems and the necessary interchangeability of components require measurements of known accuracy or compatibility in a variety of quantities. The purpose of this document is to present the hierarchy of measurements for various units that are derived from national standards and disseminated through the ESF Instrument Branch. This information should enable the users of measuring equipment to better know the capability of their equipment and to have confidence in the results obtained by specifying the level of calibration desired.

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